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GEOLOGIC REMOTE SENSING OVER THE COTTAGEVILLE, WEST VIRGINIA, GAS FIELD

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16. Abstract

Remote sensing of geologic features was investigated for the purpose of exploration for gas reserves in the eastern Mississippian-Devonian Shales. The Cottageville gas field in Jackson and Mason Counties, West Virginia, was used as a test site for this purpose. Available photographic and multispectral (MSS) images from Landsat were obtained; also 4-channel synthetic aperture radar and 12-channel MSS in the range between ultraviolet and far infrared were gathered by the Environmental Research Institute of Michigan over the test site. The images were first interpreted visually for lineaments. Then the images were enhanced by many different digital computation techniques in addition to analysis and enhancement by optical techniques. Subtle, interpretative lineaments were found which could not be enhanced to an obvious level by the procedures used. Two new spatial enhancement procedures were developed.

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ERIM

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1.0 SUMMARY

The purpose of this investigation is to apply remote sensing to find surface geologic features which indicate potential gas fields in the eastern Mississippian-Devonian shales and to develop procedures for reconnaissance exploration. Remote sensing includes airborne imaging radar, and airborne and satellite photography and multispectral imagery. This work is part of the Eastern Gas Shales Project of the Department of Energy.

Underlying a substantial portion of the eastern part of the United States, the eastern shales represent a potential major source of natural gas. If remote sensing can be used for reconnaissance the more costly forms of exploration could be used more efficiently and effectively. The placement of the more costly forms of exploration, such as surface geophysics and exploratory wells would then be aided. Much imagery of the eastern shales region is available at comparatively low cost.

A test site was selected and available remote sensing images of the site were acquired. Also radar and multispectral imagery were gathered by aircraft flights. The imagery was enhanced and analyzed by many interpretive techniques. Visual interpretation and a variety of optical and digital enhancement procedures were applied to the imagery.

The Cottageville gas field in Jackson and Mason counties, West Virginia, was chosen as the remote sensing test site by Morgantown Energy Technical Center, which is pursuing a concentrated geophysical and geological investigation of this field. The producing shale lies under 3000 ft (915 m) of sediments, the vegetated surface of which is eroded to produce hilly terrain with relief up to 500 ft (152 m). The field lies over a portion of

the Rome trough (an aulacogen), a large buried graben which runs northeastward from Kentucky through western West Virginia into Ohio and Pennsylvania. The higher producing wells in the Cottageville field follow a line roughly parallel to the Rome trough. It is speculated that fractures form conduits and reservoirs for gas from the shale, and that the fractures in this field are related to the Rome trough. However, except for microfractures in exposed rocks, no fracturing, faulting, or structural deformation has been found at the surface in the neighborhood of the Cottageville field. Also, the relationship between surface manifestations and conditions at pay zone depth are not known.

Because of the linear nature of fractures, the analysis was focused upon enhancing lineaments. Interpretative lineaments were found, most of which trended in a preferred direction. By "interpretative" it is meant that the interpretation of the lineament is tenuous and not fully demonstrable. To enhance the features in the various images, a variety of digital and optical techniques were used. Two new spatial processes were developed for the purpose of enhancing lineaments.

Image enhancement, although making the lineaments more apparent to some observers, did not make them obvious. Thus the enhancement did not "prove" the lineaments actually exist. The interpretation is still tenuous and not fully demonstrable after all the enhancement procedures were used. The optimal enhancement was the edge-enhanced color composite of three Landsat bands.

Remote sensing identifies surface conditions. In this investigation the relationship between conditions found at the surface and those at pay depth cannot be validated at this time. For unknown subsurface conditions, a validation would require an obvious result where the gas field can be displayed as substantially different from the surrounding region. This result was not achieved. For known subsurface conditions a validation could be based on subtle surface lineaments being related to known subsurface faults or fractures directly below them with downward continuity from the surface.

Because the subsurface structural conditions are not currently known in the Cottageville field, the usefulness of interpretative lineaments found near the field from remote sensing cannot now be validated. Knowledge of near-surface effects of fracturing is required through geophysics or other means.

It was found that small-scale synoptic satellite imagery was more useful than large scale airborne imagery. With the smaller scale imagery lineaments could be traced across randomly oriented stream beds. The few long lineaments which were found trended mostly in the direction of the strike of the Rome trough. The various digital and optical enhnacement techniques used on such challenging imagery gave much experience with and many insights into the use of computer enhancement in the Appalachian plateau.

2.0
INTRODUCTION

Many types of remote sensing were applied to a test site of a producing gas field in the Mississippian-Devonian eastern shales. The object was to specify procedures and to evaluate the use of remote sensing in exploration for gas reservoirs in the eastern shales. Available imagery was acquired, and synthetic aperture radar (SAR) in addition to multispectral scanning imagery (MSS) were gathered by aircraft flights over the test site. Subtle lineaments which were tenuous and subject to individual interpretation were visually discerned on the images. A variety of optical and digital techniques were applied to the imagery to enhance lineaments and other geologic features. The test site had no surface-mapped geologic features such as faults or folds and was typical of a large region in which the eastern shales were found.

The Cottageville field, located in Jackson and Mason counties, West Virginia (Figure 1), was chosen by Morgantown Energy Technical Center as the test site for this investigation. The wells in this field are shown in Figure 2. The highest-producing wells are close to a line which runs through the center of the field at about N 40° E. The terrain is vegetated with deciduous and conifer trees, brush, and approximately 50% agricultural fields. It is characterized in the U.S. Department of Agriculture (USDA) Soil Survey (1961) as "moderately deep to deep mixed soils on strongly sloping to very steep uplands and foot slopes; mainly red, fine textured soils". The elevations vary from about 600 ft (183 m) to 1000 ft (305 m) above sea level within the Cottageville field, which is about 10.5 km long in the NW direction with about 4 km maximum width. Typical terrain of the Cottageville field can be seen in Figure 5 of the USDA Soil Survey (1961).

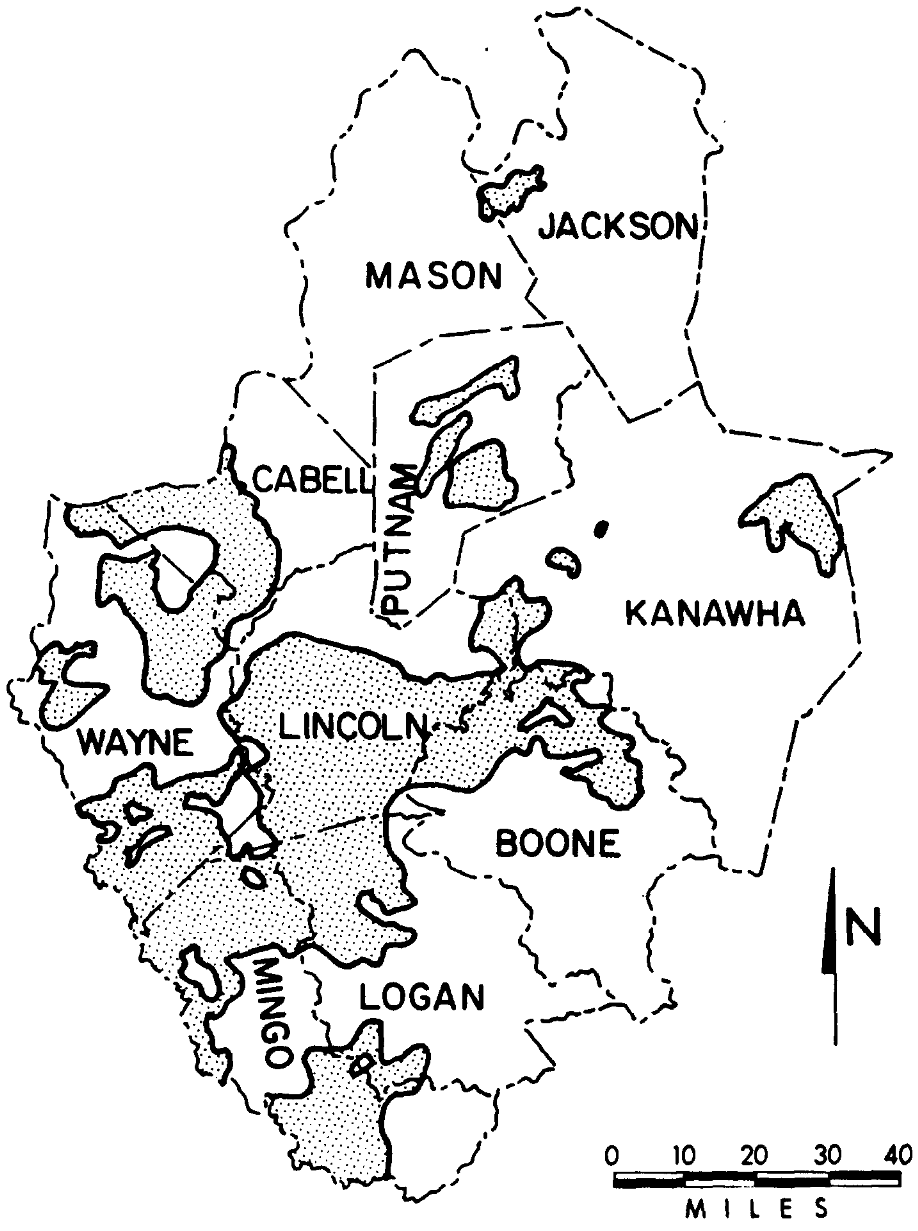

FIGURE 1. LOCATION OF THE COTTAGEVILLE GAS FIELD IN WEST VIRGINIA. (FROM PATCHEN, 1977).

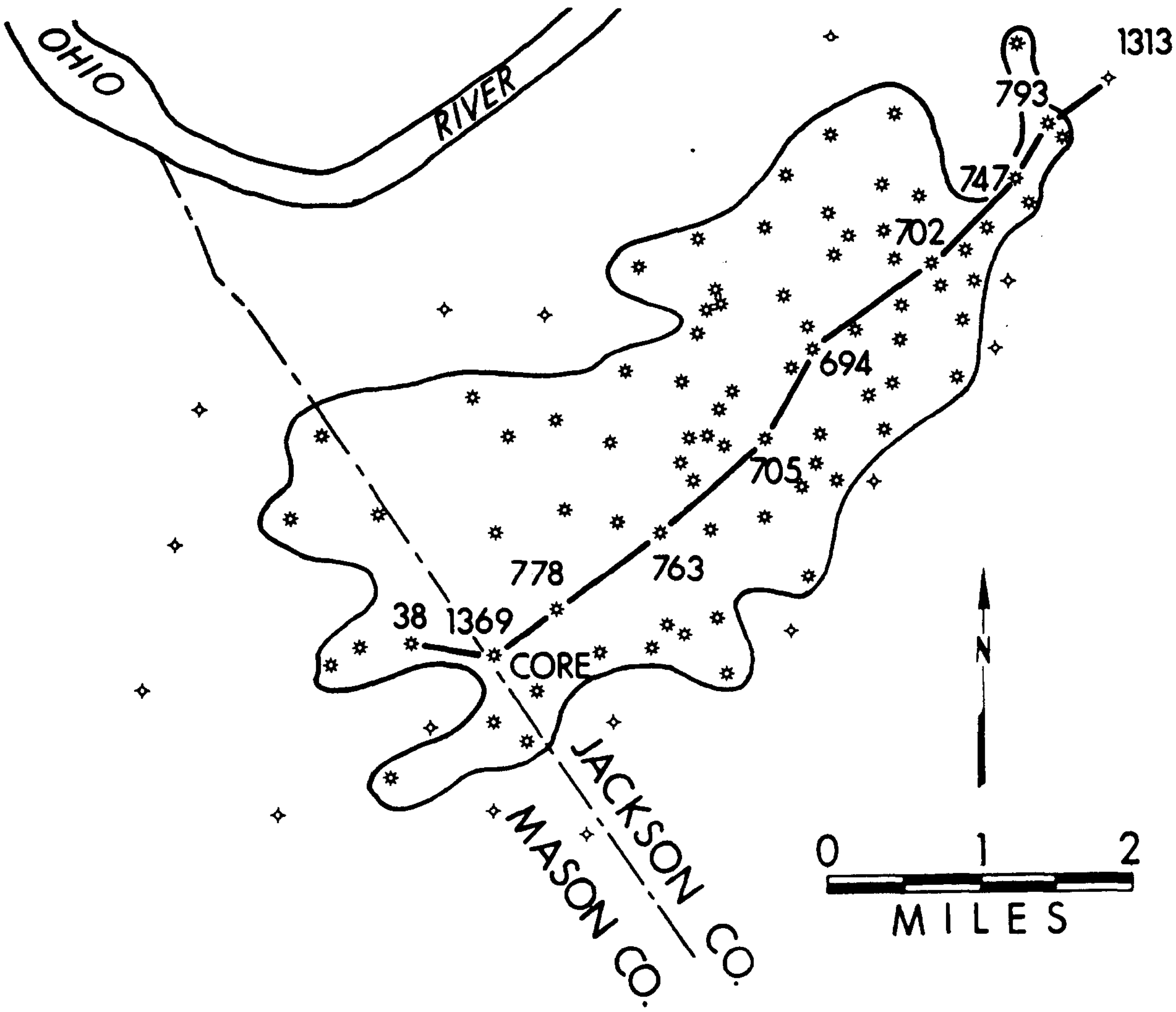

FIGURE 2. THE COTTAGEVILLE (MT. ALTO) GAS FIELD IN WEST VIRGINIA (FROM PATCHEN, 1977).

The gas producing Mississippian-Devonian shales are overlain by 3200-3400 ft (976-1036 m) of mostly Pennsylvanian sediments. The sediments are essentially undisturbed and flat-lying and consist mainly of massive sandstone, red shales, and a few limestones which often grade laterally into sandy shales and sandstones (Bryer, et al., 1976).

No geologic structures (anticlines, synclines, faults, etc.) have been mapped at the surface in or near the Cottageville field. In the Precambrian basement the Rome trough extends NE-SW under the Cottageville field. The Rome trough is an aulocagen, a wide buried graben with a series of normal faults; the trough extends from the Mississippi River to north central Pennsylvania (Harris, 1978). The Cottageville field lies on the northwest edge of the Rome trough. Martin and Nuckols (1976) suggested that basement movement on the northwest side of the Rome trough could have produced fractures in the overlying Devonian rocks which in turn could be responsible for gas production in Jackson and Mason counties. This concept is reinforced by the three-dimensional seismic studies of the basement contours which have shown that 40.9% of the production in the Cottageville field is located directly over a steeply dipping region near the top of the basement; also many of the high producing wells are so located (Sundheimer, 1978).

Thus, structurally there are large displacements in the basement at 9020 ft (2750 m) which may have produced fractures in the Mississippian-Devonian shales around 3300 ft (1000 m) but have produced no known manifestation of such structure at the surface near or in the Cottageville field. The occurrance of vertical fractures between the surface and the Mississippian-Devonian shale is not currently known. Until resistivity or other geophysical data is acquired and interpreted, the occurrance of vertical fracturing above the shale cannot be defined. There is no certainty that such fracturing has occurred, particularly so when no structural features are detectable from field mapping.

With the expectation that sophisticated remote sensing data and processing could detect surface manifestations of the hypothesized features at 3300 ft (1006 m) depth, this investigation was commenced. All types of remote sensing were used, and optical and digital analysis was applied to the available imagery. The following kinds of remote sensing data were acquired:

1. Landsat imagery and tapes
2. Skylab
3. Airborne 4-channel SAR
4. Airborne 12-channel MSS
5. Airborne photography

Imagery is illustrated in Figure 3, an edge-enhanced Landsat color composite of the region surrounding the Cottageville field. The 4-channel SAR and the 12-channel MSS were gathered by ERIM. The SAR channels included 3 cm wavelength and 24 cm wavelength, each with like- and cross polarized returns, for a total of 4 channels. The MSS included 12 spectral bands ranging from the ultraviolet to the thermal infrared. Flight lines were laid out to image two swaths of 7.5 mi x 20 mi (12 km x 32 km) (Figure 4); one swath was oriented NE-SW, the other swath NW-SE, and the northernmost 7.5 x 7.58 mi (12 km x 12 km) of the swaths were coincident. The coincident area, which includes the Cottageville field, was covered by SAR with two perpendicular look directions. Photography, SAR and MSS were obtained of the area shown in Figure 4.

Other imagery was obtained from the EROS Data Center. This included Landsat imagery in the form of tapes for a summer scene, and transparencies in addition to color composites for both summer and winter scenes. Black and white and false color IR Skylab photography and aerial photography were also obtained from EROS.

The imagery was visually interpreted by three individuals. Because the gas production is thought to be related to fractures, which

FIGURE 3. EDGE-ENHANCED COLOR COMPOSITE OF LANDSAT IMAGERY OF THE REGION SURROUNDING THE COTTAGEVILLE FIELD.

23 Sep 76
N38-54
W081-24
11523-1443
West Virginia
Edge 3+3
N

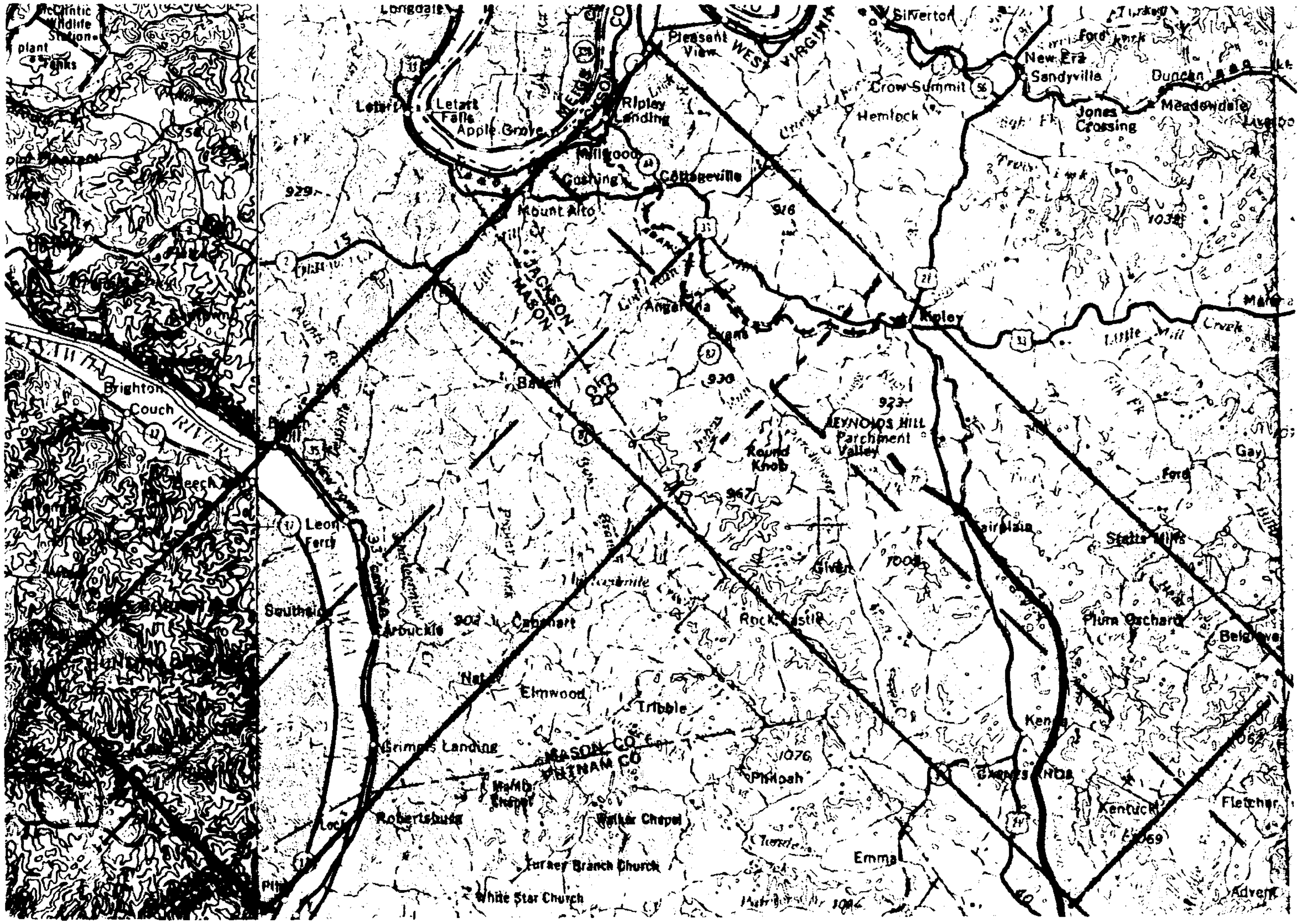

FIGURE 4. AREA OVER WHICH MSS AND SAR AIRBORNE RADAR WAS GATHERED. For Each Sensor Three Flight Lines Were Flown in Each of the NE-SW and NW-SE Directions. Double coverage in perpendicular directions was obtained over the upper portion.

tend to be linear, the interpreters searched for lineaments on the image. Interpreted lineaments were subdued and subtle, and the well-known variability and subjectivity of such interpretation (Podwysocki, 1975; Werner, 1977) was evident. Although, as expected, the different interpreters found differing lineaments, they reached a concensus on the most prominent. Figure 5 shows the visually interpreted lineaments in the Cottageville area. Those represented in heavy lines were considered the most prominent and definite, those represented in lighter lines were more tenuous. Although these prominent lineaments were found independently or agreed upon by the three interpreters, these lineaments were by no means palpable. They were subdued such that they could not be shown as actual proof of their existence.

Two previous investigations have searched for linears in the Cottageville area. Werner (1977)used Landsat, SAR, and aerial photographs at different scales to produce a lineament map of the area. Only two of the interpreted lineaments roughly coincide between Werner's interpretation and ERIM's interpretation. This lack of correlation demonstrates the subdued, subtle nature of the lineaments, and the almost subjective nature of the interpretations. Jones and Rauch (1978) have picked very short lineaments which are apparently straight hills or stream beds which extend 0.4 km to usually less than 1.6 km. No attempt to select such short lineaments was made in this investigation, as their relationship to deeply buried structures is not apparent. Small scale imagery appeared to be more useful than large scale imagery, because the short, randomly oriented straight segments of stream beds and ridges are accentuated on large scale imagery and break up the visual continuity.

After visually interpreting the imagery, a field investigation was made at the Cottageville test site. No confirmation of the lineaments

FIGURE 5. VISUALLY INTERPRETED LINEAMENTS IN THE COTTAGEVILLE AREA. Thick Lines are More Prominent and Definite, Thin Lines are More Tenuous.

was achieved. The terrain and vegetation was such that no structure such as a syncline, anticline, or fault was interpretable.

A variety of optical and digital enhnacement techniques was then applied to the imagery. The digital processes were:

1. high pass filtering (edge enhancement)
2. low pass filtering
3. directional low and high pass filtering
4. ratioing
5. level slicing
6. color slicing
7. color compositing
8. use of clustering (training sets)
9. gradient filtering (not fully developed)
10. Lommel-Seegler (directional derivative) filtering

For some of these techniques the Landsat tape was used in the ERIM MDAS interactive system for immediate color display for processing where color slicing, ratioing, and training sets were used.

The optical techniques used on the data were:

1. Fourier transform representation
2. Fourier transform directional filtering
3. Directional filtering and subsequent Fourier transforming
4. Vanderlugt filtering
5. "Spread function" Ronchi grating filtering

The interpretation of the enhanced lineaments is shown in Figure 6.

No digital or optical technique succeeded in making subtle lineaments obvious, or in "proving" that the subtle lineaments truly exist. Some techniques are inappropriate to this problem. The most effective enhancement procedure appeared to be the making of edge-enhanced color composites of Landsat bands and ratios.

ERIM

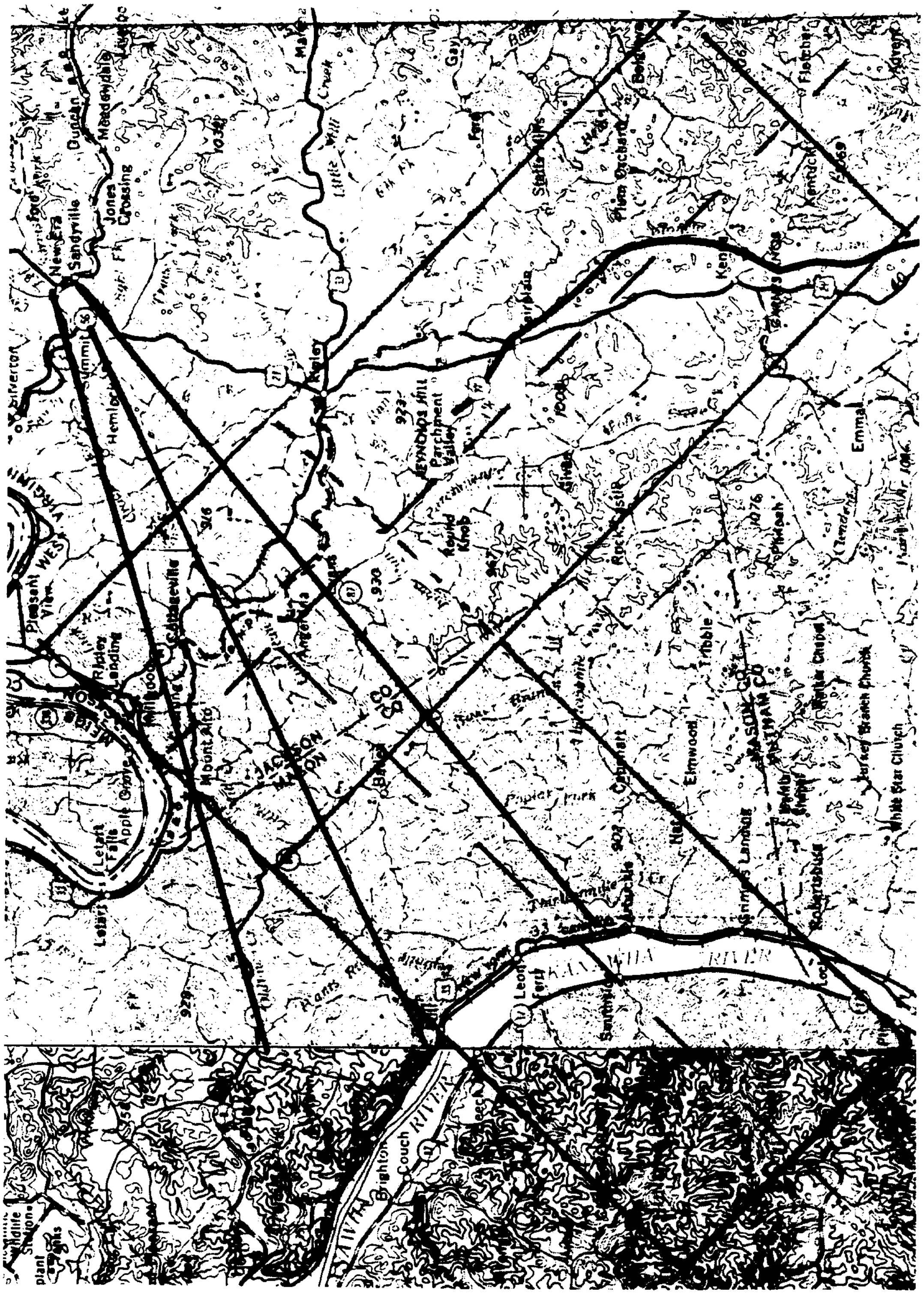

FIGURE 6. INTERPRETATION OF ENHANCED LINEAMENTS. Most Pronounced Lineaments Interpreted After Employing Various Image Enhancement Techniques.

The optical two-dimensional Fourier transform of a portion of a Landsat frame around the Cottageville field showed that higher frequency lineaments (narrower, sharper edges) lay in the N-NW direction, approximately perpendicular to the trend of the more prominent long interpretative lineaments.

Given that the surface lineaments are definite and exist, the next question is their applicability or relationship to the gas producing features which are at approximately 3300 ft (1005 m) depth. Some type of upward propagation is required to affect the surface in any way. This propagation may be in any of several forms: a fracture system extending from depth to surface, where moisture would accumulate in the fracture zone and affect the vegetation and possibly erosion; differential compaction at depth reflected at the surface, where the topography would be affected; and escape of hydrocarbons where some surface alteration and possibly vegetation is effected. In none of these propagation methods is it certain that the path is directly above the producing shale. A dip in a surface-extended fracture zone whose strike is the same as that of subsurface fractures would be located on the surface away from the vertical. Werner (1977) found no high natural open flows on or near photolineaments in the Cottageville field, and suggested that the lineaments he found may indicate fractures that allow the gas to escape.

At this time the surface lineaments cannot be related to gas production. A continuing geophysical investigation of this region will be required to achieve this relationship. For example, fractures or faults in sedimentary regions which are not perceivable at the surface can be detected by mapping resistivity (Jackson, et al., 1978; Parasnis, 1966). METC is currently funding such an effort and in the future the relationship may be achieved. Gravity and magnetic data are mostly related to the basement. Gravity grades downward almost due west 3 milligals across the Cottageville field, while aeromagnetic data shows a high on the southeastern edge of the field and grades downward northwesterly by approximately 120 gammas across the field. The relationship between these data and the perceived lineaments is not evident.

Remote sensing, a reconnaissance technology, should not be expected to be a proof of a definite existence of a geologic feature. The most economic and synoptic exploration procedure, remote sensing should be used to increase the probability of success of further geophysical methods which are more costly. For example, the next most economical exploration procedure after remote sensing is mapping resistivity, by which a suspected fault in sedimentary rocks can be confirmed. In spite of the tentative, almost subjective, nature of remote sensing lineaments found in the difficult terrain of the Cottageville field, they are useful to reduce the risk in placement of subsequent exploration methods. Although in a different region, experience in the Piceance Creek basin of Colorado has borne out the usefulness of subtle remote sensing lineaments; such a lineament was confirmed as a fracture by subsequent surface geophysical methods (Jackson, et al., 1978).

3.0

GEOLOGIC CHARACTERISTICS OF THE COTTAGEVILLE FIELD

The Cottageville field lies in Jackson and Mason counties in the western part of West Virginia. The center of the 6.5 mi x 2.5 mi (10.5 km x 4.5 km) NE trending field is at $81^{\circ}52'$W longitude and $38^{\circ}51'$N latitude. It is composed of approximately 95 wells, and the producing formation is the Mississippian-Devonian shales, 400 ft (122m) in thickness at a depth centered around approximately 3300 ft (1006 m) (Lamey, et al., 1978).

The terrain of Jackson and Mason County area is a mature topography; elevations vary from 525 ft to 1259 ft (160 m to 384 m) above sea level in Jackson county and 500 ft to 1070 ft (152 m to 326 m) in Mason county. The elevations vary from about 600 ft to 1000 ft (183 m to 305 m) within the Cottageville field area. The surface is highly vegetated with conifer and deciduous trees, brush, and about 50% agricultural fields. Small streams which dissect the area appear to have no preferred direction although they ultimately drain into the Ohio and Kanawhwa Rivers. The U.S. Department of Agriculture has classified the terrain (except for the Mill Creek floodplain near Cottageville) as "moderately deep to deep mixed soils on strongly sloping to very steep uplands and foot slopes; mainly red, fine textured soils" (USDA, 1961). The rainfall is evenly distributed throughout the year, and averages 41 in. (105 cm) annually at Pt. Pleasant in Mason County. The area was originally heavily forested, but most of the tree cover was removed during the 19th century (Krebs, 1911).

No geologic structure has been field mapped in the immediate region in and around the Cottageville field. No synclines, anticlines, faults, escarpments, intrusions, domes, etc., are observable at the surface. Also, at this time no shallow subsurface lateral structure has been identified because the requisite geophysical investigations have not been made. No known lateral structures such as faults or joints extend from pay zone depth to the surface.

Seven different soil associations are mapped by the USDA (1961) in Jackson and Mason counties. Except for the floodplains the type of soil in the Cottageville field extends continuously to about 50% of the total area of the two counties.

The gas in the brown shales is a product of organic material, and occurs in three ways (Brown, 1976):

1. that which is free in spores and fractures; production rates are a function of permeability and volume in connected space;
2. that which is absorbed on the exposed shale surface; production is related to the rate of its release from the shale;
3. and that which is within the matrix porosity; production depends on the rate and depth of diffusion through the rock to a permeable connection to a well bore.

The stratigraphy in the Cottageville field has been relatively undisturbed since Silurain time (410 MY). Outcrops and roadcuts in the area display essentially flat-lying, undisturbed sediments. The Devonian of Jackson and Mason counties is overlain by over 915 m of sediment ranging from Mississippian to Permian. The lithologies of these rocks are important to the degree to which overlying strata will reflect and transmit upward the fracture patterns or stresses which are important to successful exploration for gas. Massive sandstone, red shales, sandy shales and sandstones, and limestone make up the column above the Devonian brown shales (Pryor and Sable, 1974; Overbey, 1961).

Structurally the most important feature is the Rome trough. The northwestern edge of this large, terraced graben is thought to lie under the Cottageville field. Termed an "aulocagen" the Rome trough is described by Harris (1978) and others. The Rome trough lies in the Cambrian, and is a section of a large graben structure extending from the Mississippi River to north central Pennsylvania. The trend of the Rome trough under the Cottageville field is similar to the trend of the higher producing wells in the field. Harris (1978) describes and illustrates the development stages of the aulacogen, which have implications for the development of fractures in the overlying eastern shales.

The relief of the trough is on the order of 8,000 ft (2440 m) (Harris 1978). The Precambrian basement on either side of the trough is at 9,000 ft (2744 m) depth (Cardwell, et al., 1968). From the downwarping stage shown by Harris (1978) it can be seen that sediments above a fault can be placed in stress. Sundheimer, (1978) has interpreted seismic data to show that maximum slope occurs near the basement directly under the higher producing wells in the Cottageville field. The assumption could be made that the relief in the buried Rome trough has caused redistribution of stress in the cover, thus fracturing the shales.

Structurally the following hypothesis appears reasonable for the Cottageville field. Directly under the field at 9000 ft (2744 m) depth is a large displacement of a thousand or more feet (7305 m) on one of the faults of the Rome trough. At 3300 ft (1006 m) the producing brown shale underwent fracturing due to bending moments caused by settling (draping) over the Rome trough fault. It is thought that migration through such fractures is by far the most dominant mechanism of transport of gas to the wellbore (ERDA, 1976). Above the producing brown shale are 3200 ft (976 m) of flat-lying sediments essentially undeformed by tectonic activity. No known fractures extend from the shale to the eroded, mature surface.

4.0
VISUAL INTERPRETATION OF IMAGERY

The imagery listed in the previous section was visually inspected for lineaments. The interpreted lineaments are shown in Figure 5. The interpretation procedure used was similar to that of Podwysocki (1975). Three interpreters separately examined the imagery, and those lineaments for which there was concensus were selected as viable. However, because of the topography, soil, and vegetation in the Cottageville area, the lineaments are interpretative. They are marginally subjective. In no case is there "proof" that the indicated lineaments exist. Also, if the lineaments do exist, there is no evidence that the lineaments correspond to subsurface fractures, or are related to the shale gas production. The subdued nature of the features preclude the certainty of their existence as fractures or as indications of subsurface features.

The mature surface of the region, with flat-lying strata dissected by streams, presents an appearance in which judgements in interpreting significant lineaments must be made without firm references. Most streams have linear or near linear segments, some of which are separated but collinear. The decision as to these segments forming a lineament which might have significance for fracturing at 3300 ft (1006 m) depth is subjective. The number of segments, the total length, and the appearance and contrast with respect to the surrounding area all influence the interpreter, who is aware that random orientation of stream beds could produce apparent lineaments which have no significance for subsurface conditions. The orientation of the streams could be entirely independent of subsurface conditions.

Because of these surface characteristics the large-scale imagery, gathered from low-flying aircraft, was not as useful as the small-scale imagery obtained from satellites and high-flying aircraft. The imagery gathered by ERIM was large-scale imagery, in which relatively short segments of streams and ridges are visually obtrusive. Figure 7 is a mosaic of the NE-SW and NW-SE SAR images of Cottageville, while Figure 8 is the test site imaged in MSS band 10 (1.5-1.8 μm).

Less than 5% of the total lineaments found by the three interpreters coincided. This figure is by no means unusual for such cases. For example, in the Anadarko Basin of Oklahoma Landsat imagery interpreted for lineaments by four geologists coincided 0.4% for four interpretations, 4.7% for three, and 17.8% for two, and between two professional groups final interpretation of lineaments coincided 20% of the time (Podwysocki, 1975).

In Figure 5 the lineaments are labeled as to their prominence. The thick lines are the most evident, and the concensus lineaments. The thin lines are the tenuous lineaments which were marginally observable and for which concensus was not necessarily reached. The most prominent lineament is denoted by an asterisk. The scale ranges from 1 (all of the thin lines) as the least prominent to 10 as the most prominent. The degrees of prominence are judgmental, being based on the number of different images on which they appear, their persistence across oblique and perpendicular features, their general perceptibility, and, finally, the agreement among the interpreters.

The most prominent (or rather least elusive) lineament, labeled by an asterisk in Figure 5 trends N45°E; its nearest distance to the center of the Cottageville gas field is 8.1 mi (2.4 km), and most of the gas field is south of this lineament. The higher producing wells in the Cottageville field trend N45°E and the Rome trough in this area trends N45°E (Harris, 1978). Thus the three trends of the lineament, the higher producing wells, and the trough are closely aligned.

The NW edge of the Rome trough is not precisely determined. However, significant slopes in the strata directly above the Cambrian

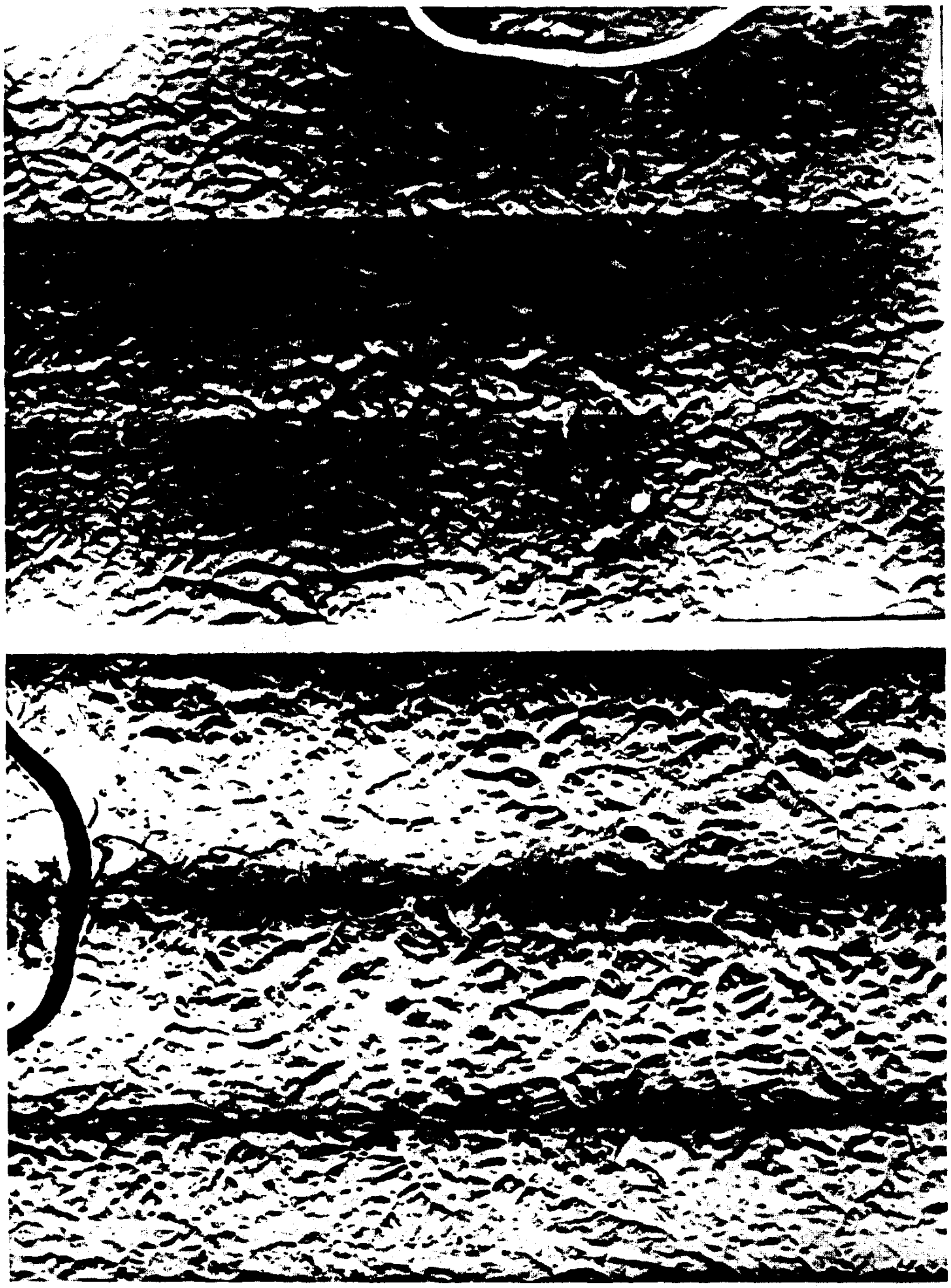

FIGURE 7. MOSAICS OF NE-SW AND NW-SE SYNTHETIC APERTURE RADAR IMAGES OF THE COTTAGEVILLE FIELD TEST SITE. Three Flight Lines were Flown in Each Direction. Radar wavelength 3 cm with horizontal - transmitted and recieved polarization.

FIGURE 8. MOSAIC OF COTTAGEVILLE FIELD REGION IMAGED IN MSS BAND 10 (1.5-1.8 MICROMETERS).

have been interpreted by seismics (Sundheimer, 1978). The steepest slopes were found directly under, and extended in the same direction, as the highest producing (natural or induced flow) wells in the field. It was hypothesized that these steep slopes were directly over one of the faults in the Rome trough.

The seismic survey described by Sundheimer (1978) is the only geophysical investigation in the region of the Cottageville field. The results of this seismic survey give no information about the immediate subsurface features (between the surface and the shales at 3200 ft (976 m) but only information at a depth of approximately 9000 ft (2744 m).

Other than the similar general trends and close proximity of the lineament, higher producing wells, and Rome trough, there is no confirmation of the interpreted lineaments being significant. One could postulate that the lineament is a result of a fracture zone propagating to the surface from depth. Slight rubblization within the fracture zone could cause surface weakness and consequent surface erosion, hold more water and consequently affect the vegetation, enable migration of hydrocarbons or minerals to the surface, or cause a slight topographic variation at the surface. All these effects could produce a detectable change at the surface along or above a fracture line.

Of the remaining prominent lineaments in Figure 5, some trend in the same direction as the most prominent lineament, and some are close to perpendicular to its trend. The investigation of Werner (1978), the only previous remote sensing investigation in the Cottageville area concerned with long lineaments, produced a set of different lineaments from those shown in Figure 5. Only two lineaments are of similar position and direction in Werner's and ERIM's interpretation. The lengths are different, however.

Figure 9 is a diagram of the number of lineaments found in 1 mi^2 (2.6 km^2) blocks of the test area. The lineaments include both concensus

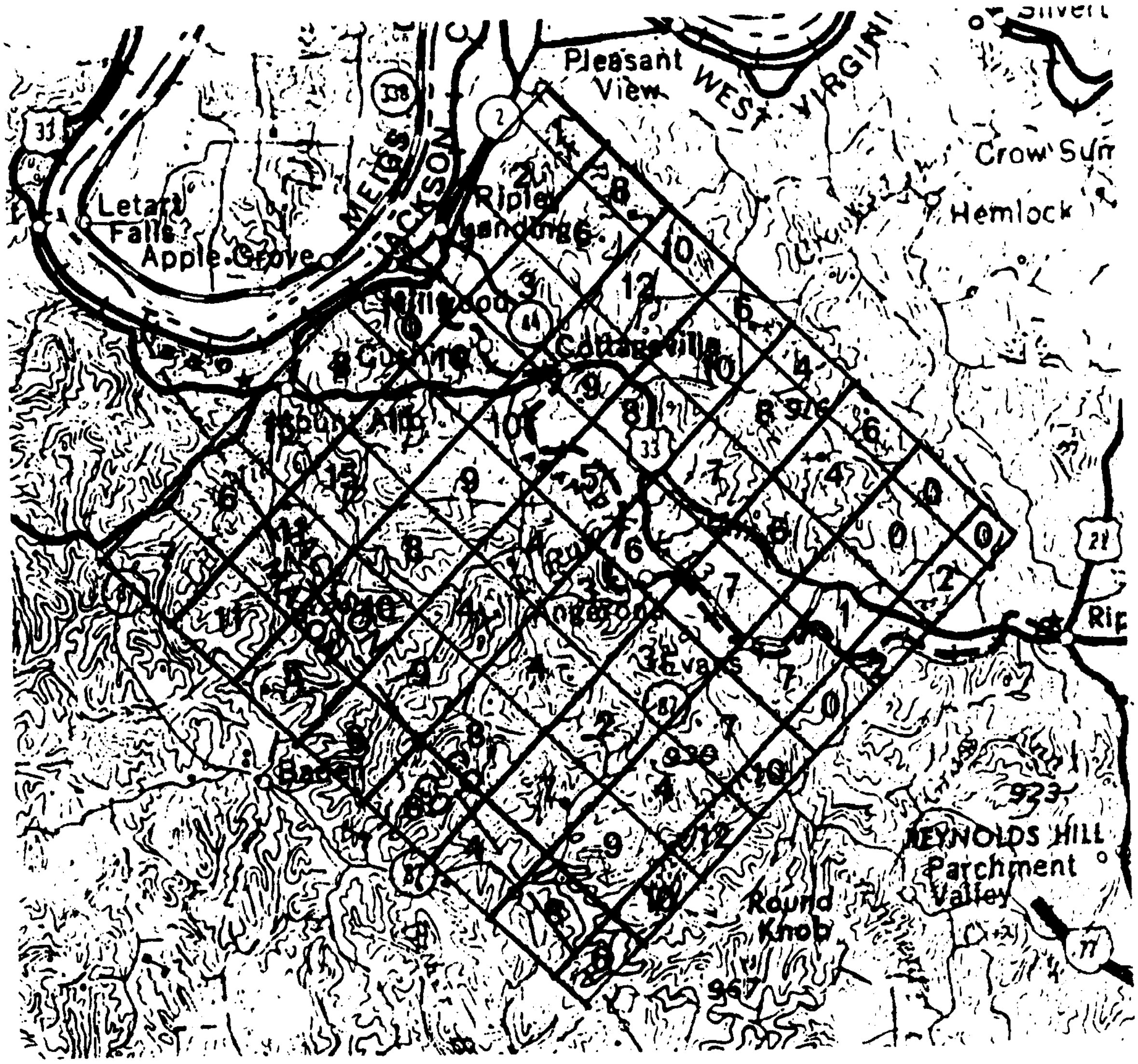

FIGURE 9. DIAGRAM SHOWING NUMBER OF INTERPRETED CONCENSUS AND NON-CONCENSUS LINEAMENTS IN 1 MILE^2 (2.6 km^2) BLOCKS OF TEST AREA SURROUNDING COTTAGEVILLE FIELD.

interpretations. Diagrams such as this are made to find concentrations of fractures which may indicate subsurface fracture on previous structural activity. This diagram is considered to be inconclusive for interpretation.

5.0
COMPUTER ENHANCEMENT OF COTTAGEVILLE IMAGERY

The bulk of the work on this contract was expended on attempting to significantly enhance lineaments in the Cottageville imagery. Enhancement of interpretative lineaments to palpable lineaments was not achieved.

Two reasons for the lack of significant enhancement can be suggested: first, the interpreted lineaments were so subjective, that they were essentially "created" by the interpreters, so that their existence is in doubt. Second, the lineaments were so subtle that the computer techniques were inadequate to significantly enhance or identify them.

Either or both of these suggestions can be valid. At this time there can be no answer. The lateral structure in the Cottageville field is not known, so that a validation of the interpreted lineaments is not possible. Also, the computer techniques may have been inadequate to enhance such linears. The latter reason requires some explication, to place perspective on computer processing.

Although computer analysis is referred to often in the literature, and is thought to be quite sophisticated, the fact appears to be that it is not highly developed. This fact was learned during this investigation. The techniques have been developed in the last few years, and are often inadequate. Smith (1977) states this fact as, "Various information extraction techniques and automatic data processing methods fail as yet to meet information requirements." Also, the lion's share of effort of computer enhancement of remote sensing has been in classification. Comparatively little effort has been expended on spatial processing, which this investigation requires.

Despite the extensive effort on classification analysis, new algorithms and procedures are currently being developed because previous

ERIM

analysis has been inadequate. For example, the LACIE project, which was instituted to estimate wheat crops from Landsat imagery (MacDonald, 1975) requires development of new algorithms and procedures for classification. New sampling, clustering, strata definition, preprocessing and labeling have recently been developed because the former procedure and algorithms have been inadequate for classification purposes (Cicone, et. al., 1979). The fact of advancement in procedures and algorithms should not be surprising, because the demands for classification analysis of remotely sensed data are continuously becoming more stringent.

The demands on spatial processing are also becoming more stringent. The computational identification and enhancement of lineaments requires new algorithms and procedures. Spatially the human eye is more perceptive of patterns and gradations, particularly in the presence of obscuring and distracting patterns, than is a machine. It is our opinion that the human can perceive valid features that cannot be identified or enhanced with current algorithms and methods. In fact, in attempting machine enhancement spurious features can be generated, as was found by Podwysocki (1975). The incapacity of currently available linear enhancement procedures and algorithms to enhance lineaments found in the Cottageville imagery led ERIM to develop two new algorithms.

Despite their subtlety, the lineaments interpreted for Cottageville imagery are valid, insofar as they should be used for their proper purpose -- reconnaissance. Remote sensing is intended for the purpose of aiding in the placement of geophysical measurements. It is the principal scientist's opinion that computational enhancement procedures will be developed which can bring out interpretative features.

The digital and optical enhancement techniques which were used on the Cottageville data are described below. Each established enhancement technique is described briefly and illustrated if pertinent. References will be given for more extensive descriptions of the computer techniques. The two new computer enhancement techniques which were explored during this contract will be described in greater detail, because it is thought that they may contribute to the evolution of computer enhancement. One of the new techniques is described in Appendix C, a reproduction of a paper presented to an ASP meeting.

Each digital enhancement of Cottageville imagery is described below:

1. High pass filtering for edge enhancement

This procedure was performed on Landsat and radar data. In this procedure a block of two dimensional sample (pixel) values is averaged, and the difference between the center sample and the average is found. This difference value replaces the original value of the center sample in the image reformation. The procedure is described in Chavez, et al., (1976). The purpose is to intensify edges which lie along lineaments, thus making the lineaments more obvious.

The color composite of Figure 3 was processed in this manner. For this composite a 3 x 3 (9 elements) array of pixel values was averaged, and the difference between the average and the value of the center pixel was found in each of three Landsat bands (bands 4, 5, and 7). The filtered bands were then used to form the color composite. This procedure was one of the most effective used. The interpretative lineaments appeared less subtle on this composite than on unprocessed color composites or on individual bands of Landsat imagery. It should be reiterated that, although in the opinion of the interpreters that the lineaments were more apparent (less subtle), they were by no means made palpable by this high pass filtering procedure.

This procedure was also applied to radar data. However, due to the scale, stream beds and cultural features only were enhanced. The larger, wider and more pervasive features which more probably indicated lineaments were obscured. Figure 10 illustrates one result of this type of filtering on a radar image.

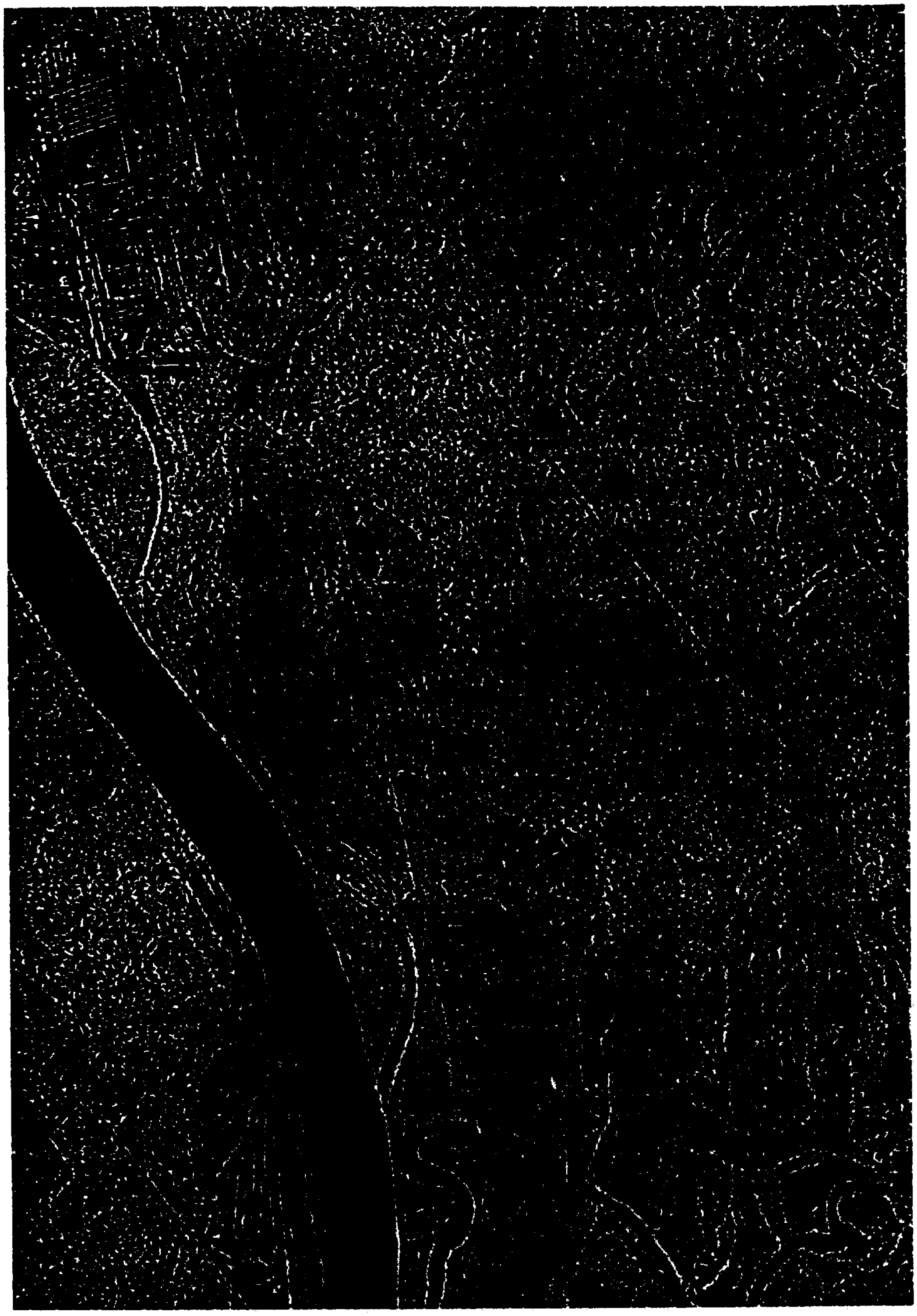

FIGURE 10. HIGH-PASS FILTERING OF PORTION OF SAR IMAGERY (λ=3cm) OF COTTAGEVILLE REGION. Note Enhancement of Cultural Features, Particularly the Large Industrial Plant on the Ohio River.

2. Low-Pass Filtering

This procedure is equivalent to "smoothing". An array of pixel values is averaged, and the pixel value at the center of the array is replaced by the average. Sharp edges are subdued and more gently varying features are enhanced. Sometimes this procedure is used to preprocess data for other kinds of processing, such as ratioing. Noise, artifactual variations which are sometimes high amplitude and sometimes random and sporadic, are reduced by low pass filtering. This procedure was used as an enhancement technique, but with negligibly useful results. However, it was necessary to use low-pass filtering in preprocessing to reduce the effects of noise when using other procedures. Low pass filtering is described by Chavez, et al. (1976). An example of low pass filtering is shown in Figure 11.

3. Directional Low and High Pass Filtering

This type of filtering is asymmetric. Instead of averaging over a square array as in procedures #1 and #2, a direction is chosen, and the array is made rectangular. For example, a low-pass filtering in one direction would consist, say, of averaging a number of pixels in a segment along a single row to produce the value for the pixel at the midpoint of the segment. Such a procedure is for the purpose of enhancing lineaments parallel to the row, because those lineaments perpendicular to the row (in the direction of the columns) will be "smeared out" by the averaging.

If high-pass filtering is performed along the row, the lineaments perpendicular to the row would tend to be enhanced or sharpened. The high-pass filtering would again be accomplished by replacing the value of the pixel at the midpoint with the difference between this value and the average of the segment. This type of filtering is described by Chavez (1976).

An example of this type of filtering is shown in Figure 12.

FIGURE 11. LOW-PASS FILTERING OF SAR IMAGERY (λ=3cm) OF COTTAGEVILLE FIELD. 9×9 Smoothing.

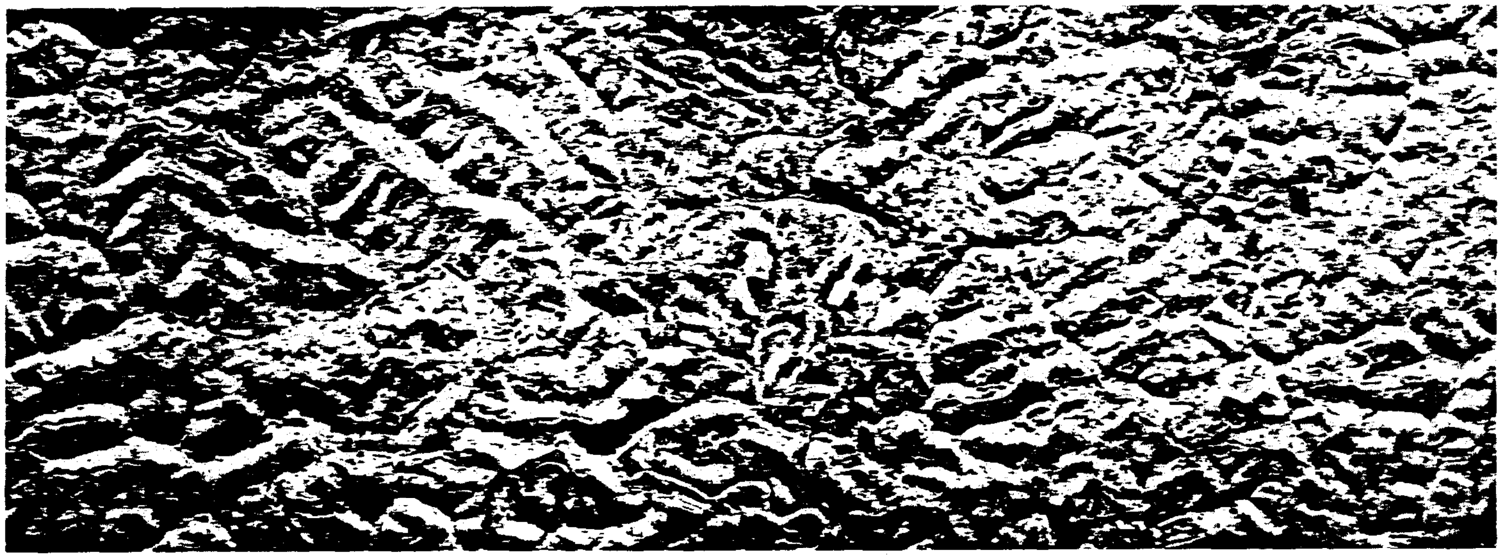

FIGURE 12. DIRECTIONAL LOW-PASS FILTERING OF SAR (λ=3cm) OF COTTAGEVILLE FIELD.1×12 Smoothing.

4. Ratioing

Whenever more than one channel of a scene is imaged, ratioing can be performed to enhance the differences between the channels and subdue those features which are the same on both channels. Ratioing is performed by dividing the value of each pixel in one image by the value of the corresponding pixel in another image. The ratioing is performed only after "dark-object subtraction" is accomplished to remove biases in the images. The bias may be due to natural causes such as haze from the sun, or to instrumental and processing causes. Ratioing is used to enhance subtle differences between channels. Because visual comparison between images (in contradistinction to spatial evaluation) is relatively difficult, ratioing is particularly useful. Also, the more obvious features which appear the same on two images are neutralized. A ridge or bluff, for example, is sometimes removed in the resulting ratioed image. With this removal extremely small differences in the spectrum of different vegetation or rock types can be magnified to observable differences. A suite of ratios can be used to again make comparisons -- a color composite formed of three ratios is an example. Ratioing of multispectral imagery is discussed by Vincent (1977).

A color composite of ratios 4/5 (blue), 5/7 (green), and 6/7 (red) of the Landsat frame including Cottageville is shown in Figure 13.

Ratioing was performed on Landsat, airborne MSS and SAR imagery. Color composites were made on sets of Landsat ratios, on which the interpretative lineaments were detected, although the most prominent lineament appears to be centered 5 km north of the Cottageville field rather than the 3.5 km found with band color compositing.

The ratio of airborne MSS and SAR was not diagnostic of lineaments or other features. The MSS ratioing enhances vegetative differences at large scale. These were not indicative of lineaments or areas of high gas production. Similarly for the ratioing of 3 cm and 24 cm SAR images (the discrimination of agricultural crops was pronounced, however).

FIGURE 13. COLOR COMPOSITE OF RATIOS OF LANDSAT FRAME INCLUDING COTTAGEVILLE.
Band 4/Band 5 (blue), 5/7 (green), and 6/7 (red).

23 Sep 76
N38-54
W081-24
11523-1443

N

23 Sep 76
N38-54
W081-24
11523-1443

N

FIGURE 13. COLOR COMPOSITE OF RATIOS OF LANDSAT FRAME INCLUDING COTTAGEVILLE.
Band 4/Band 5 (blue), 5/7 (green), and 6/7 (red).

5. Level Slicing

The redistribution of the assignment of output gray levels to ranges of values of input pixels is termed level-slicing. Commonly an image is represented by a comparatively larger number of integral input values, say 256, and the output on photographic film, graymap, or cathode ray tube is often limited to a smaller number of integer values, say 64 or less. A straightforward means of representing the 256 values would be to assign 4 input values equally to the output values: the lowest four input values would be assigned to the darkest output level, and each increasingly higher set of four input values assigned to each increasingly lighter output up to the level where input values 253-265 are assigned to the lightest output level.

However, the above straightforward means is not optimal for representing the image. One has the choice of representing the large number of input values in many ways so that desired contrasts are enhanced in the image. This is accomplished by assigning an arbitrary (but limited) number of input values to each output value. For example, there may be an insignificant number of pixels with values between 0 and 193, and none of these located in a region or on a feature of interest to the interpreter. In this case one output level could represent input levels 0-193, and each remaining output level (63) could then correspond to each remaining input value (194-256). In this way distinctions can be made in input levels of interest. It can be seen that there are many ways of performing this redistribution or "level-slicing".

Level slicing is usually based on histogram, a frequency distribution of all of the available pixel values. One of many representations is to assign output levels to correspond to equal areas under the curve representing the histogram. Other representations are based on slope, on displaying an "edge" between two closely related objects, and by interactively changing the level slicing to bring out desired contrasts while viewing a CRT presentation. Level slicing is discussed by Taranik (1977).

6. Color Slicing

Similar to level slicing, which refers to the redistribution of output gray levels, color-slicing refers to redistribution in terms of color. Three primary color "guns" are used to display the entire visible color spectrum. The relative intensities of the individual colors are then chosen to enhance desired features in an analogous manner to that used for gray levels. Color and hue represent the image.

7. Color Compositing

A means of presenting multichannel data in one image, color compositing has become quite popular for Landsat data. Three channels are commonly used, with each channel represented by a primary (or near primary) color. Landsat bands 4, 5, and 7 are usually composited, each band represented by a separate color. The resulting composite often shows different types of vegetation and soils in different colors. The 1:250,000 color composites of entire Landsat frames are often cosmetically attractive, and sometimes useful for geological interpretation. Color composites are described by Taranik (1977). The color composites of Figures 3 and 11 were constructed in this way.

8. Clustering (Training Sets)

Relative magnitudes of multichannel data depend upon the spectral characteristics of the object or group of objects in a scene. A concept for visualizing the relative values of the data channels is that of a vector in n-dimensional space, n being the number of channels used. This vector will be based on the magnitudes of each channel. The magnitudes are summed vectorially so that the "location" of the tip of summed vector indicates the relative contribution of each channel.

This location is then taken as the center of a region or "cluster" of values produced by the spectrum of an object or set of objects in a scene.

A "training set" (or portion of the image) is selected from the image in which the objects to be tested for are known or thought to be known to be dominant. The spectrum of the training set is then measured by the resultant vector formed by the relative magnitudes of the channels. The rest of the scene is then tested to see if the spectra are similar. If portions of the image are similar within a specified amount, they are classified to be the same type of object or objects as within the training set.

Several measurement and decision criteria are used in making the decisions about whether a portion of an image is sufficiently similar to the training set to be classified as the same object or objects. These are rather abstruse and sometimes arbitrary. References on training sets, clustering algorithms, and decision criteria are found in Taranik (1977).

9. Combinations of Methods

Typically more than one method will be employed. Some combinations are low pass filtering before performing ratioing, level slicing of ratios, color composites formed of different ratios, clustering of sets of ratios.

Each of the above digital analysis techniques were employed on at least one kind of image of the Cottageville field. The list is not exhaustive of the possible techniques, which are continually being developed (Cicone, et al., 1979). It should be noted that, except for the three simple kinds of filtering, the techniques tend to enhance spectral composition rather than spatial features. Most of the development of digital image analysis has been focussed on spectral composition -- for the identification of agricultural crops, for example. Comparatively little analysis development in the remote sensing field has been expended on the delineation of spatial features and shapes. The latter appears to be the type of analysis required for interpretation of surface features indicative of eastern shale production at depth.

10. Two New Approaches to Lineament Enhancement

Because spatial analysis was required, and the available techniques appeared inadequate to enhance or verify the suspected linears in the test site, two methods of spatial processing were developed. These appear to be new contributions to remote sensing analysis.

The first method employed artificial illumination on actual imagery similar to the employment of the equation on actual topographic data presented by Bateson, et al., (1975). They describe the computation of shadows and appearances that would be produced by a sun at a given azimuth and elevation and a given viewing angle. From digitized contour map data (available from USGS for all of the conterminous states) the slope in the direction of the sun is found for each digitized sample. A shaded relief image is then formed for the digitized sample. A shaded relief map produced from the Charleston quadrangle is shown in Figure 14. This map was produced by Geospectra, Inc., as a Topo Image (copyright name).

Because this process is directionally sensitive it can be used to enhance directional features such as linears. However, it directionally falls of by the cosine and only rejects completely those features which are perpendicular to the direction to be enhanced. Figure 15 is an optical two-dimensional Fourier transform of Figure 14, which can be viewed as density rose diagram of the directional predominance of linear features. The gradual diminution, proportional to the cosine of the direction, can be seen.

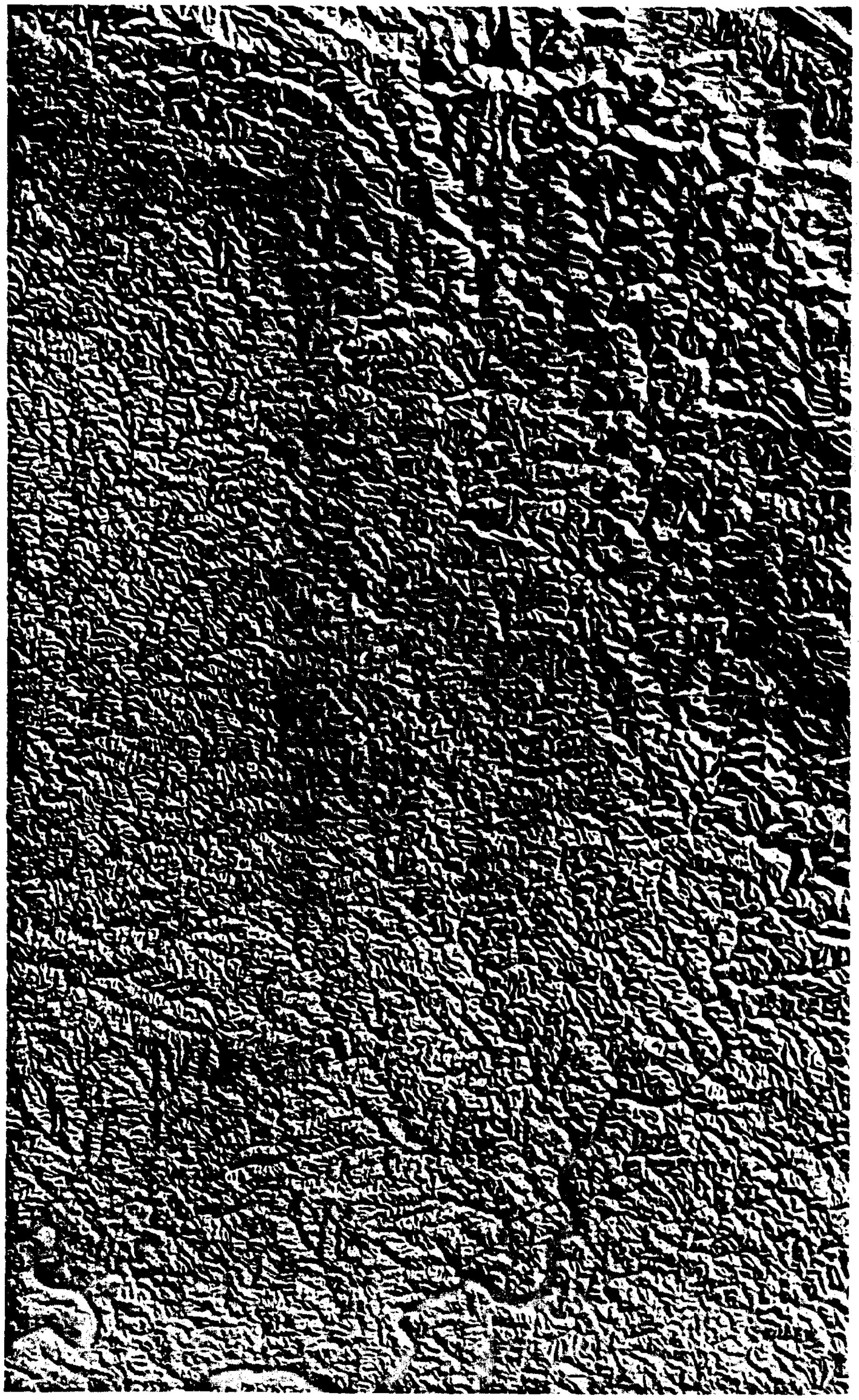

FIGURE 14. SHADED RELIEF MAP OF CHARLESTON QUADRANGLE PRODUCED FROM DIGITIZED ELEVATION CONTOUR DATA. Simulated Sun at 30° in Northwest. Produced by Geospectra, Inc., under copyright name "Topoimage".

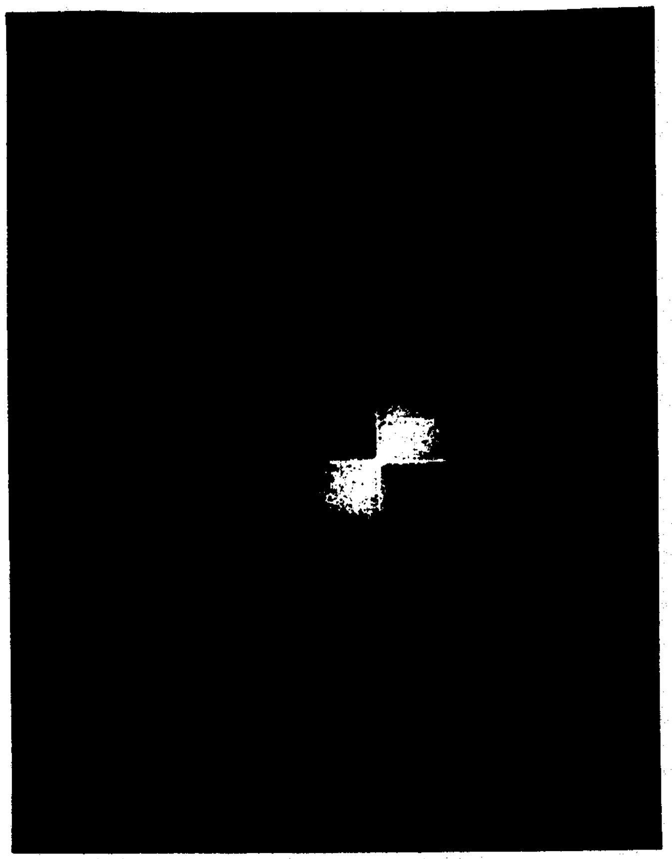

FIGURE 15. OPTICAL FOURIER TRANSFORM OF IMAGE SHOWN IN FIGURE 14. Note the Directional Attenuation Until No Slopes Are Indicated Parallel to the Sun's Direction.

The new aspect of the application of the Lommel-Seegler equation is that it is applied to actual imagery, rather than topographic contour data. The meaning when applied to topographic data is obvious. However, the meaning, when applied to imagery, is not clear, other than its use in enhancing lineaments predominantly lying in one direction. Figure 16 shows this process applied to Landsat imagery of the Cottageville region.

The slow attenuation with direction combined with the difficulty of enhancing suspected Cottageville lineaments when using the Lommel-Seegler equation provided the impetus to find a more selective means of directional filtering, the second new approach to lineament enhancement.

A means was found which also employs the slope. The direction of the maximum slope, which is the direction of the gradient, is related to lineaments in the following way: the lineament exists because of a continuing change in value transversely along the lineament. For example, this change in value occurs as elevation in topography and as intensity in an image such as Landsat. In fact the persistence of the transverse changes in values actually is the only characteristic which defines the lineament. Along a lineament the direction of the gradient will be, therefore, transverse to the direction of the lineament. Using a simple computation to find the direction of the gradient in all pixels in an image, a directional filter can be constructed to select gradient directions which are required to form lineaments in the perpendicular direction.

In this way lineaments are directionally filtered. The filtering is similar to two-dimensional Fourier transform filtering, except that the gradient filtering process is much more economical, and no ringing occurs as in the Fourier transform.

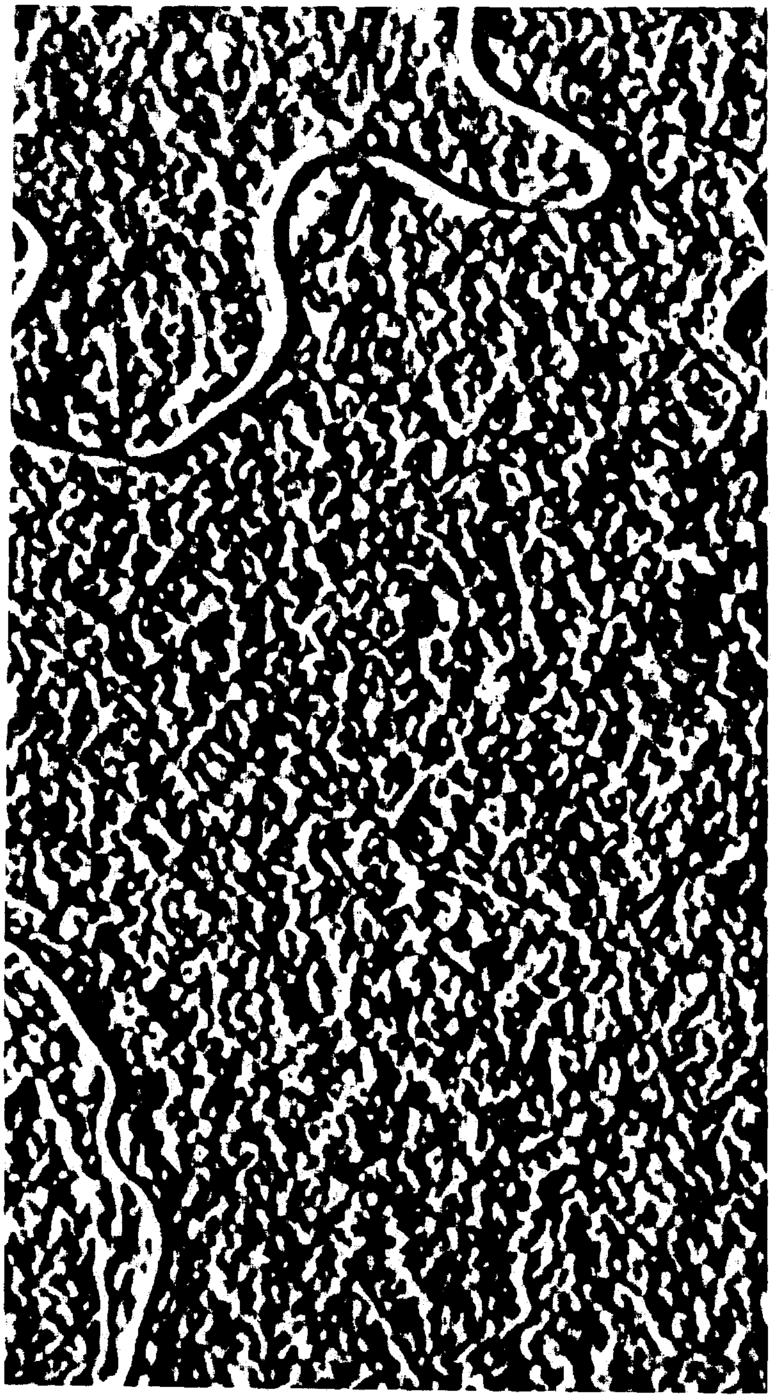

FIGURE 16. SHADED RELIEF "MAP" OF LANDSAT IMAGERY OF COTTAGEVILLE WITH SIMULATED SUN 30° ABOVE HORIZON IN THE EAST DIRECTION.

The gradient filtering method, considered to be a new contribution, was written in the form of a journal article, and is to be presented at the 1979 Convention of the American Society of Photogrammetry and the American Congress on Surveying and Mapping in Washington, D.C. The paper is included as Appendix C of this report.

Optical processing used in this project is described below. Unlike digital processing, in which numbers represent the image, optical processing employs a visual replica in the form of a photographic transparency or print, or displayed on a cathode ray tube. Light impinges on the replica and the reflected or transmitted light is then passed through devices which either analyze or filter the image. Theoretical techniques can be used with either coherent or incoherent light.

1. Fourier Transform

A Fourier transformation of a replica is obtained by diffraction. Conventionally a plane wave of monochromatic light passes through a replica, and the distribution of the light due to Fresnel diffraction at an infinite (farfield) distance defines the two-dimensional frequency of the replica. When the diffracted light is gathered by a lens, the farfield Fresnel distribution occurs at the focal plane of the lens. The addition of such a lens forms the well-known Fraunhofer diffraction set up, where the distribution of light at the focal plane of the lens is the two-dimensional transform of the replica.

The usual optical Fourier transform set-up consists of a laser, a microscope objective to focus the laser light on a pinhole for approximation of a point source of light, a lens placed a focal length away from the pinhole to collimate the light (that is, to make the light form a plane wave), the replica, and following this a lens to focus the light in the Fourier transform plane. Because the diffractive process is phase sensitive, the film thickness variations of the replica can cause noise interferences. To nullify the noise effect of the film, a "liquid gate" is desirable. The liquid gate consists of two optical flats sandwiching the replica within a fluid with index of refraction similar to that of the film.

A more elemental optical set up which is more flexible and produces less noise with imperceptible degradation of accuracy can be made with one lens only. The pinhole is imaged by one lens, with whatever magnification is desired. The pinhole image is in the Fourier transform plane. The replica is then placed anywhere that the light beam is sufficiently large between the pinhole and its image. The distance from the replica to the image of the pinhole then determines the scale factor of the Fourier transform, a factor which can be adjusted by simply moving the replica along the light beam. Also, if a large scale factor is desired this may be accomplished by large magnification in producing the image of the pinhole (when the lens is relatively close to the pinhole). This contrasts with the conventional two-lens plane-wave optical set up where the scale factor is fixed by the focal length of the lens. In addition to the flexibility of the scale factor, the reduction of glass in the diffractive system reduces noise, because dust, dirt, and glass defects are present in and on lenses.

The light distribution in the Fourier transform is complex -- having both phase and amplitude. However, only the energy can conveniently be measured, although filtering can be performed which takes advantage of the complex nature of the Fourier transform. The means of measuring are visual, photographic film, and scanning or arrayed photo receptors, each of which produce a voltage output proportional to the intensity of radiant light. The three means of measuring are energy sensitive, and insensitive to the phase of the light.

The Fraunhofer diffraction pattern (Fourier transform) is symmetric about a point indicating zero frequency in both directions. This point is the image of the pinhole. The frequency scale is the distance from this zero point in any direction of the diffraction pattern. The direction indicates the orientation of features in the replica. Figure 15, the photograph of the Fraunhofer diffraction Fourier transform of the shaded relief map made from the topographic data of the Charleston quadrangle, illustrates the transform. The intensity of linears falls off by the cosine from the perpendicular to the direction of the sun angle in any such image. The Fourier transform in Figure 15 clearly shows this directional attenuation.

Optical Fourier transforms are described in Cutrona, et al. (1960), and Jackson (1964a, 1964b).

2. Fourier Transform Filtering

The Fourier transform is an intermediate step in imaging with coherent light. If a lens is added to the above-described system, the replica can be imaged. This means that between the replica and its image is a Fourier transform of the replica. In this plane the representation is in frequency and orientation, without regard to the position of features in the replica. Selective attenuation of light in this plane can, therefore, act as a filter for both spatial frequency and orientation of features in the replica.

To filter for lineaments, wedge-type filters can be placed in the optical Fourier transform plane. If the features in the replica are aligned within a given angle, they will cause diffraction in the Fourier transform plane within the same angle, but rotated 90°. The diffraction will then be within a wedge with this angular extent. A passband or stopband wedge can be placed at this location in this plane. A passband, for which the wedge is transparent, allows the imaging of only those lineaments in the replica which are aligned so that their diffracted energy is within the transparent wedge. Conversely, for a stopband the wedge is made opaque and the remaining area in the Fourier transform plane is transparent.

Diffraction also occurs in the Fourier transform plane, causing degradation in the image. Interference fringes in the image are caused by the edges of the wedge. Also, with the photographic type of replica used for remote sensing images, most of the light is undiffracted so that extremely bright light intensity is produced at the center of the Fourier transform filtering plane; the slightest diffraction from this source will cause interference fringes throughout the image.

When direction only is to be filtered independent of frequency, a white light source may be used, because the direction of diffraction is independent of the wavelength. With such a source the degradation in the image caused by the edges of the filter is reduced. However, a difficulty arises in producing a small "point" source of light without reducing the light level to a semi-usable level. The basis for white light filtering is described by Jackson (1965).

A Fourier transform filtered image of the Cottageville area is shown in Figure 17.

3. Vanderlugt Filtering

The Vanderlugt filter is a complex optical filter in which the output is a correlation function in the image plane with its center corresponding to the location of the feature in the replica. The filter interacts with the light distribution in the Fourier transform plane in such a way as to indicate where a feature is located in the replica. For conceptualization, consider an array of letters and numbers on a replica, with the Vanderlugt filter constructed to pass the letter "g". Whenever "g" is found in the replica, a bright spot

FIGURE 17. FOURIER TRANSFORM FILTERING OF LANDSAT FRAME INCLUDING THE COTTAGEVILLE AREA. Direction of filtering N45°E, Angular Extent of Filter 10°.

will occur in the image plane (Vanderlugt, 1964). Mitchel and Roth (1969), have applied the Vanderlugt filter to geologica formations and water waves. However, in Mitchel and Roth's replicas the lineaments were rather prominent and easily perceivable in the original image. This type of filtering was attempted, but not found applicable to the subtle linears suspected in the Cottageville region. Much more than other kinds of optical processing, the use of the Vanderlugt filter requires experience and a high degree of skill.

4. The Ronchi Grating

The Ronchi Grating, or a square wave transmission grating, is a set of opaque parallel lines on a transparent backing such as glass or plastic. The uniform widths of the opaque lines are equal, and the separation between the lines is the same as the widths; thus a "square wave" of light transmission is formed transversely to the direction of the lines. Light is diffracted by the Ronchi grating in a direction perpendicular to the direction of the lines on the grating. The farfield distribution of the diffracted light is precisely that of the Fourier series of a square wave.

When an image is viewed or photographed through a Ronchi grating the diffracted light will be spread out in one direction, but will be undisturbed in the perpendicular direction. This diffraction will then tend to blur out lineaments in the image which are parallel to the lines of the grating, thus accentuating the lineaments which are perpendicular to the lines in the grating. In optics, this is known as an astigmatic spread function.

The grating thus acts by selectively "smearing" out the lineaments in one direction and leaving the perpendicular lineaments relatively undisturbed, which is a means of enhancing the undisturbed lineaments. However, because the grating produces a spread function which is the

Fourier transform of a square wave, the directionality is frequency selective. The distribution of the grating spread function is not a solid line, in which case all frequencies would be eliminated. An example of the frequency selectivity is shown in Figure 18, in which a fan is imaged through a Ronchi grating. Note that in a narrow angular region the lines at all frequencies are imaged, but in other directions the lines are selectively attenuated (blurred out). The spatial frequencies of the fan lines are inversely proportional to the radial distance.

The Ronchi grating thus enhances lineaments in one direction while subduing, but not eliminating, lineaments in other directions.

Because of the smearing in one direction, the enhanced lineaments are stretched, i.e., smeared parallel to their direction, so that they appear longer than they actually are in the image. In the Cottageville area with the mature surface, very short lineaments such as ridges or stream segments can be smeared into one another, creating the appearance of a long, significant lineament. Long "assembled" lineaments can be seen in all directions in the Cottageville area. For this reason the Ronchi grating method should be used with great care.

To obtain Rochi-filtered photographs of imagery, the grating can be placed directly in front of the camera lens. Ambient light can be used. Also, an image can be viewed by holding the grating a few inches in front of the eye.

Viewing images through the grating appears to be the best use of this device. The construction of artifactual lineaments as discussed by Podwysocki (1975) occurs in the Cottageville area when Ronchi-filtered photographs are taken. However, when the images are viewed through the grating apparent lineaments can be immediated compared with

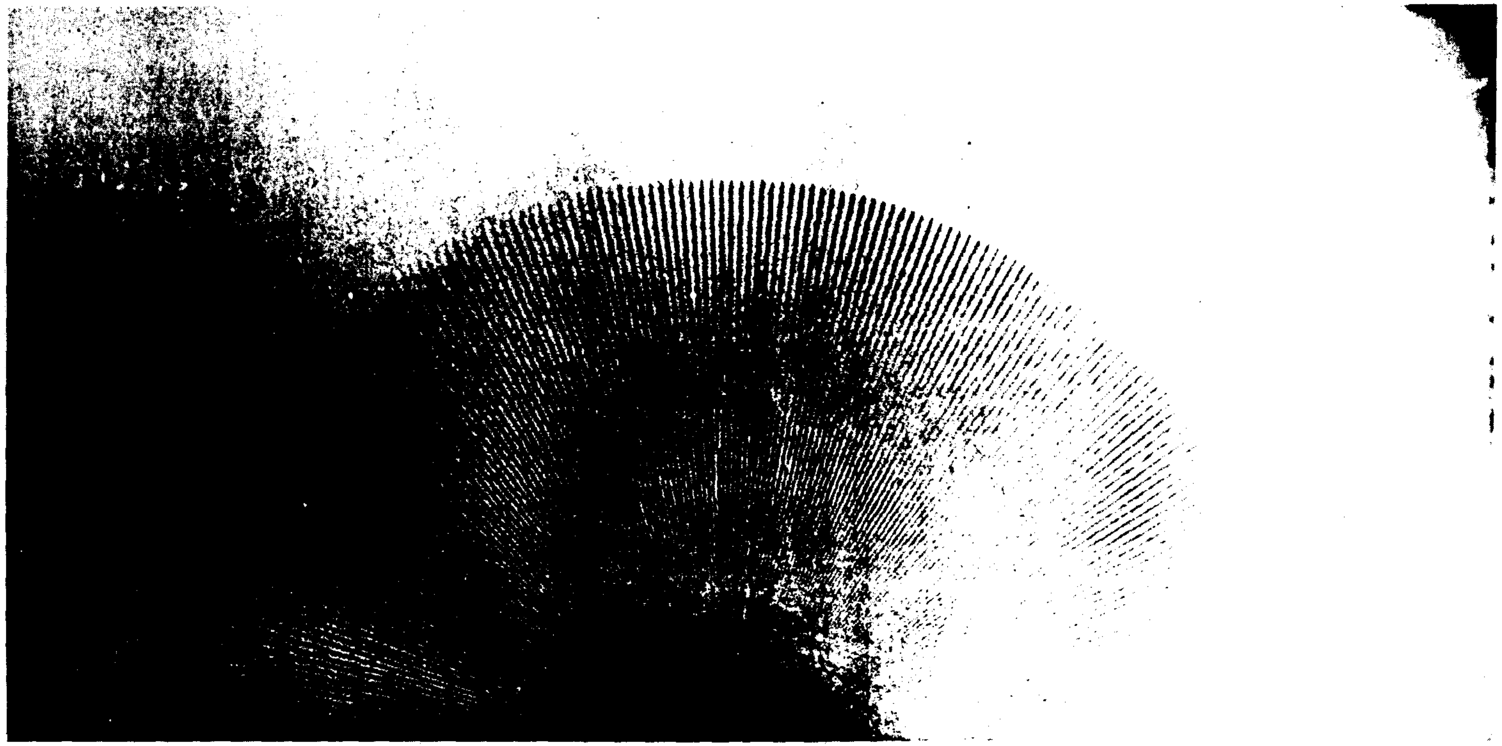

FIGURE 18. IMAGE OF A FAN-SHAPED CONFIGURATION WITH RADIAL LINES AT 1° ANGULAR INTERVALS. Note passage of complete radial lines in one direction, but selective attenuation in other direction. Two aligned gratings, 7.9 and 9.8 lines/mm, separated by 2cm, placed directly in front of 50mm lens of SLR camera.

the unfiltered image. Also, the composition of the lineament can be discovered by rotating the grating slightly. Conversely, a suspected lineament on the unfiltered image can be tested by viewing it through the grating and judging the relative enhancement with respect to other apparent lineaments. The capability of interaction with the image is the optimal use of this device.

Figure 19 shows a Ronchi-filtered Landsat scene which includes the Cottageville area.

The Ronchi grating method is described by Pohn (1970), and an application to an Appalachian region is shown by Elder, et al., (1974). These authors employed a single grating. Because of the segmented nature of the spread function produced by the grating, two aligned superimposed gratings were employed and were spaced a few centimeters apart. Comparisons showed the two gratings produced more definitive filtering with a more uniform background than produced by a single grating. The spacings of the lines were 7.9 lines/mm and 9.8 lines/mm.

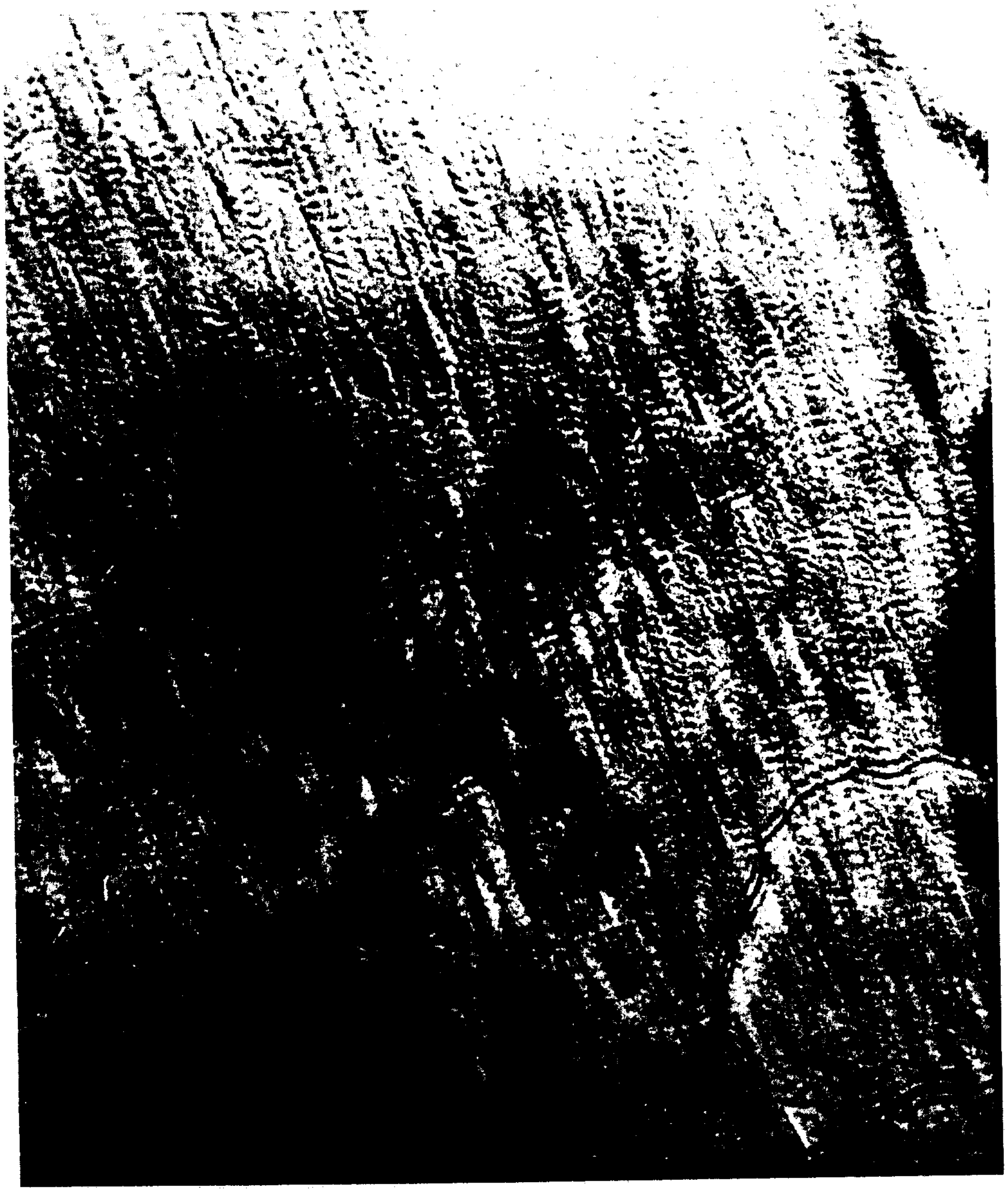

FIGURE 19. RONCHI-FILTERED LANDSAT SCENE INCLUDING COTTAGEVILLE. Two Gratings (7.9 and 9.8 lines/mm used). Aligned to NE-SW direction.

6.0
INTERPRETATION OF ENHANCED IMAGES

It should again be emphasized that the enhancement procedures did not result in producing obvious features of subdued interpretative features. It must be accepted that there is a probability that the visually interpreted lineaments were subjective, some probability that the lineaments, in fact, do not exist as a geological feature. Alternatively, there is a probability that the interpretative lineaments do exist, and that the machine procedures we used were not sensitive, selective, or noise-immune enough to identify and validate the suspected linears. Suitable machine processing for areas like Cottageville may not have been developed at this time.

On the other hand, the interpretative lineaments could be shown as more palpable lineaments with optical Fourier transform and Ronchi grating techniques, but many other lineaments in all directions were found (or created) which appeared to be as definitive as those along the interpretative lineaments. Therefore, the interpretative lineaments could not be considered as selected or enhanced by these means.

The large-scale imagery (SAR, airborne MSS, and low altitude aerial photography) did not lend itself to enhancement. The mature, dissected nature of the surface prevented this type of imagery from being useful in discovering pervasive lineaments. The dissection of the surface by erosion overwhelms other features.

The small scale imagery, principally Landsat, was more useful in inferring lineaments. Figure 5 shows the enhanced interpretative lineaments which are most prominent. These trend NE-SW, with the most prominent lineament lying between the Cottageville field and the Ohio River. This lineament was found (along with many others) by Fourier transform filtering (Figure 16) and by Ronchi grating filtering (Figure 18). With CRT enhancement procedures these linears appeared to be more prominent. The color composites of three ratios of Landsat data also indicated these lineaments.

Given the fact that remote sensing data should be viewed as reconnaissance data, these interpretative linears are evident enough so that they should be used for placement of ground based geophysical investigations. When faults or fractures are to be explained in a region where no field work has shown such features at the surface, interpretative remote sensing features, even when controversial, offer the best placement of geophysical measurements.

7.0
DISCUSSION

The results of this investigation are not conclusive. No basis for the validity of remote sensing for aiding in the exploration of eastern shale gas can be made. If definite lineaments, even after computer enhancement, had been found, the basis still could not be validated. The nature of the test site and the fact that geophysical measurements to find subsurface fracturing have not been obtained, lead to two reasons for non-validation.

First, the test site provides no reference from which to make inferences. The region has no surface or subsurface-mapped structural features such as faults, synclines, anticlines, or domal structures. In addition the surface is mature, with erosional ridges and streams giving much relief in pseudo-random directions. Each stream or ridge which maintains its direction for a kilometer or so could be termed a "lineament." The strata are essentially flat-lying. Although seismic studies indicate a dipping interface just above the basement, no information is given about the sub-surface. The gravity and magnetic data also refer to the basement. However, the edge of the Rome Trough underlies the field and is thought to affect productivity.

Thus no reference is provided. Remote sensing is often used to show similarity of features or composition between a known scene and an unknown scene. This powerful procedure was not possible here. The possibility also exists that no surface manifestations of the gas field are present.

Second, given the interpreted lineaments, there is currently no way to evaluate them. They do not lie directly over the field, although they do trend similarly to the field and the Rome Trough. Their nature is undetermined, whether a fracture, fault, syncline, anticline, or the effect of escaping hydrocarbons.

Thus this region presents two obstacles: no reference on which to base, compare, and extend the interpretation, and no means of confirming the interpretative features which were found. If the area or the central portion of the gas field had been shown to be different from the surrounding area, the validity of remote sensing could have been shown.

Even though only interpretative lineaments were found which could not be enhanced to appear as obvious, or concensus, lineaments, the probability of aiding exploration is high. Remote sensing should be considered a reconnaissance procedure, and should not be considered to be a definite indication of conditions. It should be the first step in exploration to improve the placement of the more expensive groundbased geophysics. It should not be the single basis of well drilling before geophysics is applied. Given a potential gas producing area, the time and expense of further investigation may be reduced by a knowledge of the possible lineaments. The probability of economic savings in exploration is increased by using interpretative lineaments unless there is some more compelling reason to locate initial ground-based explorations elsewhere.

This investigation was an excellent opportunity to try many kinds of digital and optical analysis on an intransigent problem. Although features were not enhanced to a concensus level, comparative evaluations could be made on the enhancement methods. Of the optical methods, only one can be recommended for use: the visual use of the Ronchi grating. The grating should be used in a dynamic, interactive way to search for lineaments which can be immediately discerned with the naked eye. It can indicate more lineaments than actually exist, but also can be used to emphasize some overlooked lineaments. Filtering and photographing the result of both the Ronchi and Fourier transform produces too many spurious lineaments to be worthwhile. Photography of the Fourier transform showed trends in a N20°E direction, but these were not tracable to particular lineaments, and were interpreted to be due to high frequency stream beds of short lengths. However, the precise measurement of the Fourier transform was not achieved in this program. Photocell array measurements may be of greater usefulness. Trends of master joint sets may be indicated by this method.

The digital computations were more beneficial. Color composites, edge enhancement, and ratioing were beneficial in aiding visual interpretation. Specifically directional enhancement such as smoothing in one direction did not appear to aid in interpretation. The two new methods were developed toward the end of the program and were not throroughly tested.

It emerged clearly that, for this area and problem, small-scale, synoptic imagery was more useful than large-scale imagery. The reason for this is that the mature surface is dissected by pseudo-random erosional features. These erosional features overwhelm the pervasive lineaments which are manifested by subtle tonal gradations extending across several smaller, sharper features. The measurement of the density of short lineaments interpreted on the large-scale imagery was felt to be inconclusive.

The interpretative character of the lineament is emphasized by the fact that Werner (1977), who conducted a thorough investigation of the lineaments in the Cottageville area, found only two which roughly coincided with our major lineaments. Of these two, one is the lineament we considered to be the most pervasive and predominant. It runs N 45° E passing 3.5 km north of the axis of the Cottageville field. There is no reason to prefer the lineaments we interpreted over those Werner interpreted. In fact, Werner was more conversant with the area than we. The salient point is that the interpretation of lineaments between separate interpreters usually correlated only in a minority of cases (Podwysocki, 1977). In the Cottageville case 2 of the 4 lineaments chosen by ERIM as significant correlated with a previous investigation. This correlation would indicate sufficient significance to concentrate geophysical exploration along these two interpretative lineaments.

Regardless of the inability to enhance suspected lineaments to the point of obviousness so that a concensus of their existence could be obtained, it may be possible to enhance such lineaments in the future. Many different kinds of enhancements were attempted. However, new methods are being developed (Cicone, et. al., 1979), and possibly in the future enhancement of the subtle to the obvious may be possible. Because of the wide variation of interpretation between interpreters even in areas where surface features are evident (Podwysocki, 1975) objective machine analysis or enhancement is desperately needed. We are confident that it will come.

Despite the seemingly negative aspect of some of the foregoing discussion, this investigation has been very valuable. The current limits of enhancement were found. We even were motivated to develop two new methods, which, if not solving the Cottageville problems, may be useful for other investigations. As shown by many examples in many fields of endeavor, attacking an intransigent problem, gaining experience, and then backing off to a more amenable problem as a fresh beginning, has often proved to be very fruitful. It is anticipated that this investigation will prove fruitful in such a way.

8.0

RECOMMENDATIONS

The following recommendations are based on the experienced gained in the performance of this contract. They include future work for application of remote sensing to eastern shale exploration, the selection of enhancement procedures, and needed research in the image analysis discipline.

1. A continued investigation in the eastern shales region should be based on a test site with surface feature(s) which are known and identifiable by field mapping and related to gas producing formations. With these features as a reference the extension to more subdued features of similar nature should be investigated, and the limits to the current capacity of remote sensing defined for this purpose. Also similar features should be evaluated elsewhere.

2. To verify and to properly use remote sensing interpreted lineaments, a method of confirmation should be employed. This confirmation is required in both research and operational use. For example, a lineament often can indicate a subsurface fracture in which the rubble zone would be of anomalous resistivity. Mapping resistivity across the location indicated by the lineament would provide an economical confirming procedure.

3. Small scale imagery such as Landsat should initially be used to discover lineaments in areas such as Cottageville. The mature, dissected surface of essentially flat-lying sediments is manifested in streams and ridges which are mostly due to random erosion, and which overwhelm meaningful lineaments on large-scale imagery. It is necessary to first find lineaments which cross the smaller, sharp features and which more probably reflect deeper structural discontinuities.

4. Much of remote sensing image analysis is devoted to compositional analysis - the composition of the soils, rocks or vegetation without regard to the structure of geometry. In regions similar to Cottageville spatial processing, which has not been developed as far as compositional processing, and which enhances or defines the geometry of the image, is required. In looking for pervasive lineaments reflecting conditions from around 1000 meters depth, both types of processing are required.

5. Individual interpretation of identical imagery vary so widely that a method of reducing these variations must be found. Also, a means of evaluating features probabilistically is required. The probability that an interpreted lineament is a pertinent geologic fracture needs assignment in terms of the type of imagery and method of interpretation.

6. The limits of machine processing need to be determined. Currently it appears that visual interpretation can detect and identify more subtle features than computers, in fact, more subtle features than computers can even enhance. To find these limits requires extending the computer analysis from obvious to more subtle features.

7. Optical processing should be used only as a visual aid. The Ronchi grating should be used in a dynamic, interactive way so that possible lineaments can be suggested to the interpreter. Coherent optics present problems with noise and require much skill of the operator, whereas digital computing is essentially noise-free and is operator independent. The precise measurement of the Fourier transforms of imagery should be investigated.

8. Interpretation should be aided by a geologist with much experience in the region to be investigated. Knowledge of the subsurface, geophysical results, exploration history, trends, and surface features can then be used as a basis for enhancement and final determination of lineaments.

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ERIM

APPENDIX A
APPLICATION OF REMOTE SENSING

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APPLICATION OF REMOTE SENSING

The term "remote sensing" generally refers to airborne or satellite sensing of the earth's surface by electromagnetic radiation. The field of endeavor was started as soon as the first photographs were taken from airplanes or balloons. The use of aerial photography for geologic inferences was termed "photogeology." In the last 50 years photogeology has become an established academic and industrial discipline. Within the past 15 years MSS and SAR have been developed and used both experimentally and operationally. The advent of Landsat in 1972 has dramatically demonstrated the advance of remote sensing. Along with the new sensors, enhancement and analysis techniques have been developed for the imagery which is recorded on digital tape.

Although all types of airborne and surface geophysical sensing could properly be termed "remote," common usage does not include airborne field sensing: airborne electromagnetic (AEM) sounding and aeromagnetics are generally not included in the term. Nor are surface geophysical measurements such as gravity, resistivity, seismics, etc., included in remote sensing.

Several comprehensive texts have recently been published on remote sensing (Smith, 1977; Sabins, 1978; Reeves, 1975).

The electromagnetic spectrum and applicable sensing systems are shown in Figure 1. Remote sensing data is in the visible, near visible, infrared, and microwave regions. Three basic types of remote sensing are used: photography, multispectral scanning (MSS) and synthetic aperture radar (SAR).

MSS refers to scanning the earth's surface in separate spectral regions. Figure 2 illustrates the instrumentation and procedure. A rotating scan mirror reflects energy from transverse lines under the

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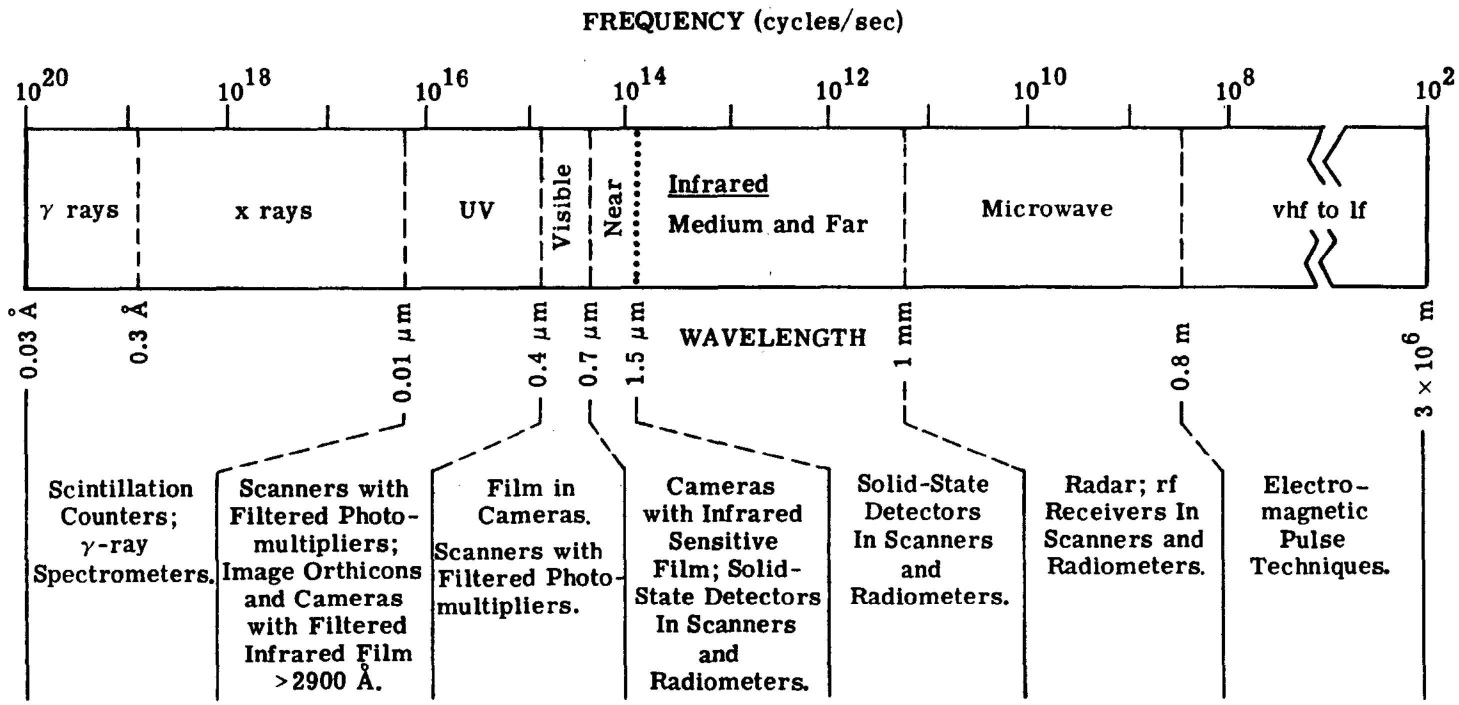

FIGURE 1. THE ELECTROMAGNETIC SPECTRUM AND APPLICABLE SENSING SYSTEMS. Adapted from Research News, Vol. XVIII, No. 8, Office of Research Administration, The University of Michigan, Ann Arbor, February 1968.

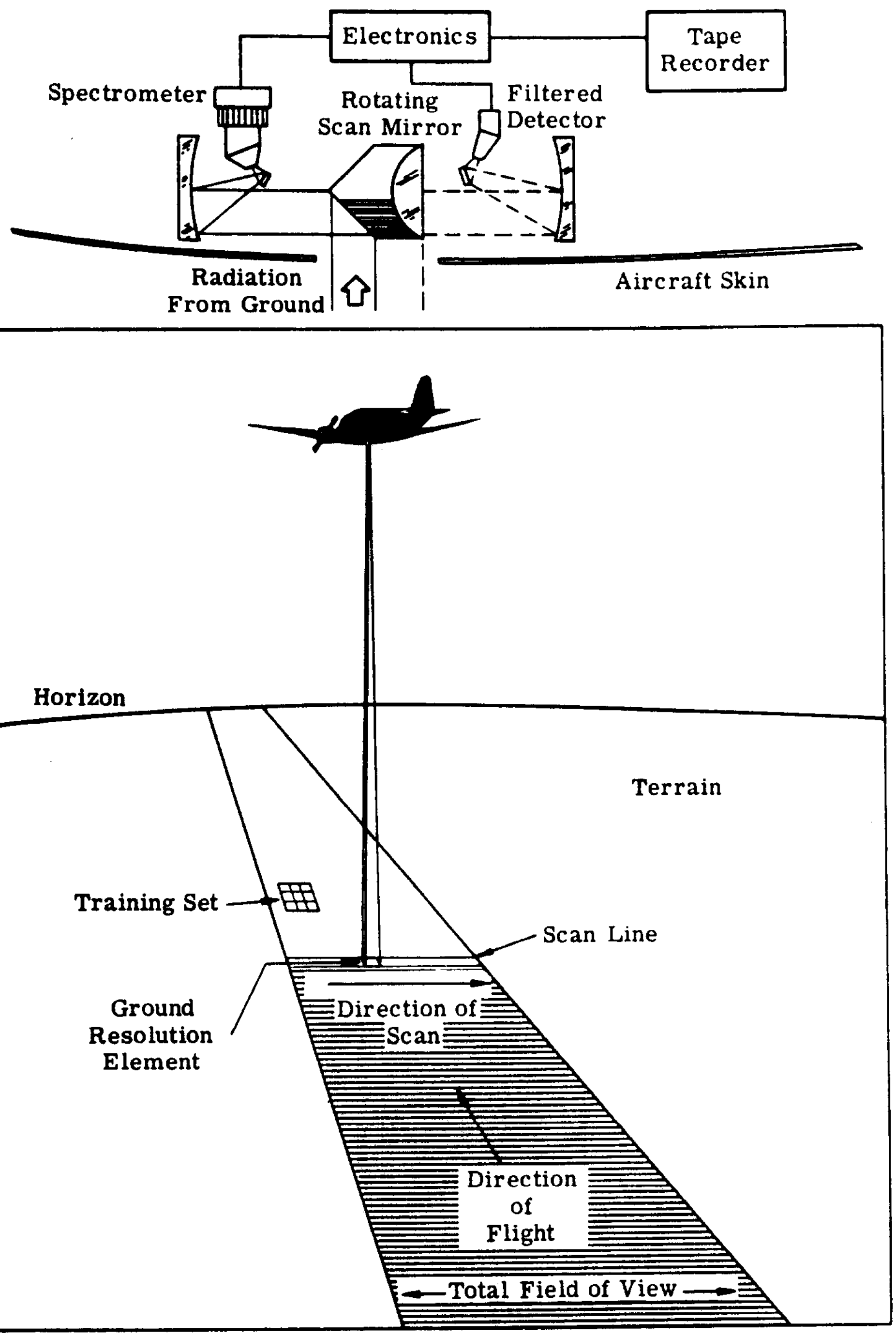

FIGURE 2. MULTISPECTRAL DATA COLLECTION

aircraft on a set of receptors, each of which is a narrow band. Landsat is an MSS channel with four bands. The Landsat bands are:

Band 4	0.5-0.6 μm	(green)
Band 5	0.6-0.7 μm	(lower red)
Band 6	0.7-0.8 μm	(upper red-lower infrared)
Band 7	0.8-0.11 μm	(near infrared)

The concept of multispectral discrimination is relatively simple. The reflectance and emittance of radiant energy by an object are wavelength dependent and usually specific for the materials and conditions of that object. In other words, different objects have different reflectance and emittance characteristics which vary uniquely over the electromagnetic spectrum. By collecting information in a number of spectral bands and by knowing or discovering the unique spectral characteristics of objects or conditions, it is possible to identify these and to distinguish one from another.

An image formed from a broad spectral range may be adequate to distinguish objects which have grossly different radiant characteristics in that range. By comparing two or more images of the same object made in different reigons of the spectrum, the chances of being able to discriminate and identify that object are increased. As the number of spectral bands is increased, additional information is available about the object of interest. If the spectral characteristics of objects are not specifically known (generally the case), it is an advantage to have a number of spectral images, because one or more will probably show tone differences between two or more objects better than others. Thus, the inherent ability to distinguish between similar objects is enhanced with an increase in the range and amount of spectral information.

To take advantage of the spectral information of a scene, the reflected and emitted radiation must be sampled in a number of discrete bands in order to get accurate representation of the energy distribution.

For this purpose, an airborne optical-mechanical scanner system, using reflective optics, has certain advantages over multiple aperture systems. First, the spectral information is recorded in electrical form on computer-compatible magnetic tape, and, therefore, certain limitations in data handling and processing inherent in photographic processes are avoided. Second, the detectors in scanner systems are not limited to the rather narrow spectral range over which conventional films are sensitive. Modern scanning systems collect data over a 0.32 - 14.0μm spectral range. However, because of atmospheric absorption, surface radiation cannot be recorded in the 2.6 - 3.5 μm and the 5.5 - 8.0 μm wavelength ranges.

Sidelooking airborne radar (SLAR), including synthetic aperture radar (SAR) as the principal kind, has imaging capabilities that complement the passive remote sensors. Although SAR effectively collects geologic information when used alone, maximum data will be obtained if it is used prior to ground studies in conjunction with other sensors, each contributing its special information. Sidelooking radar has the same limitation as multispectral scanning and aerial photography in that it provides information, often relatively detailed, about surface and very near-surface, but no information about geologic features more than a few centimeters beneath the surface, since the wavelengths have negligible penetration into geologic materials.

Sidelooking radar imagery portrays the reflectance characteristics of the terrain for certain wavelengths of the electromagnetic spectrum that are much longer than those of visible light. Significantly affecting the general radar return are surface roughness, topography (including orientation and slope of surfaces), complex dielectric constants of soils and rocks, object geometry, moisture content of the feature (especially near the surface), type and extent of vegetation, moisture content of low vegetation (such as brush, crops, and grasses), and the incidence angle, wavelength, and polarization of the transmitted radar energy. The relative value of the different parameters commonly is difficult to assess, even after a comprehensive study. Generally, several parameters contribute to the magnitude of the radar return, but one parameter may be dominant. The relative importance of each parameter depends upon the feature and region being imaged.

A surface with roughness less than the wavelength of the incident electromagnetic energy appears smooth and flat to the energy and acts as a specular or mirror-like reflector. The specular reflection may be either a strong return or a no-return, depending upon the angle at which the energy strikes the surface. Rougher surfaces appear multifaceted to the incident energy and act as diffuse reflectors, scattering energy in all directions. Diffuse reflectors return only a fraction of the energy to the antenna. Because radar wavelengths are much longer than those of visible light, many more surfaces appear smooth to radar energy than to visible light.

The surface of the earth presents an extremely varied panorama. However, only two elemental characteristics can vary in this panorama: composition and geometry. The composition can be mineral or vegetation, and the geometry can present any pattern, from the roughness and texture to the large scale patterns and trends. Remote sensing is designed to detect minute variations in composition, by the fact that comparative reflectances and emissions in the different spectral bands are dependent upon composition. For example, many different minerals can be detected and identified by comparing remotely sensed bands; also the kinds, vigor and moisture content of vegetation are identified (Vincent, 1977; Holmes and Nuesch, 1978). Microwave imagery, although dependent upon composition, is highly sensitive to small scale roughness and to topography (Rydstrom, 1967; Cosgriff, et al., 1960; Lewis and MacDonald, 1970).

Thus remote sensing is designed to detect extremely small differences in composition or geometry. In the context of the Cottageville field application, the upward propagation of fractures, if any, would be extremely subdued at the surface. This propogation would have to be manifested in a change of composition (including water content) or geometry in the form of roughness due to fracturing in the form of variations in topography. If these effects are at the surface they are marginal because they have never been observed at the surface or from aerial photographs.

Remote sensing offers the best hope of detecting such marginal surface manifestations.

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APPENDIX B

ACQUIRED AND GATHERED IMAGERY OF COTTAGEVILLE REGION

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The following is a list of the Cottageville imagery:

Acquired Imagery

1. Landsat Imagery (4-bands; 5-6, 6-7, 7-8, 8-11 μm)

   Three sets of 9x9 transparencies (4 bands)

   a. September 23, 1976, Scene ID 8552314431500
   b. February 11, 1977, Scene ID 8566414304500
   c. July 18, 1977, Scene ID 8290815083500

   Two color composites (bands 4, 5, and 7)

   a. September 23, 1976
   b. February 11, 1977

      computer compatible tapes for September 23, 1976.

2. Skylab

   a. August 9, 1973, B&W Scene ID G30A026022000
   b. August 9, 1973, CIR, Scene ID G30A027022000
   c. August 9, 1973, COL, Scene ID G30A028022000

3. NASA Aircraft-Standard

   a. December 3, 1973, CIR, Scene ID 5730015777132
   b. May 17, 1971, COL, Scene ID 6166001505322

4. Aerial Mapping - Standard

   a. April 3, 1976, B&W, Scene ID IVDLT00550404
   b. April 3, 1976, B&W, Scene ID IVDLT00550405

Gathered Imagery

12-Channel ERIM MSS, M-7 Scanner

Channel bands: .33-.38, .40-.44, .45-.49, .49-.52, .51-.57, .54-.63, .60-.72, .66-.84, .78-1.11, 1.5-1.8, 2.0-2.6, 9.0-11.4 μm.

Acquired by ERIM on October 21, 1977. Flown at 350 m elevation, resolution 8 x 8 m, swath width 6 km. Three image swaths flown NE-SW, and three swaths flown NW-SE, for lengths of 32.2 km.

The flight lines were not parallel, resulting in approximately 5% loss of coverage (12 km x 12 km) test site area.

2. 9" B&W Aerial Photography of area flown for MSS coverage. Simultaneous coverage with MSS imagery.

3. 4-channel synthetic aperture radar. Acquired by ERIM on October 21, 1977. 3 m (X-band) like- and cross-polarization; 23 cm (L-band) like- and cross-polarization. (1.6 m x 2.2 m) resolution. Swath width 5.5 km length of swath > 32.2 km. 3 swaths NE-SW and three swaths NW-SE area of coverage shown in Figure 4 of report.

APPENDIX C

GRADIENT FILTERING FOR DIRECTIONAL TRENDS IN IMAGES

GRADIENT FILTERING FOR DIRECTIONAL TRENDS IN IMAGES

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BIOGRAPHICAL SKETCHES

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Harvey L. Wagner received his BS in Geological Oceanography from the City University of New York and his MS in Remote Sensing from the University of Michigan. He is currently pursuing his doctorate at the University of Michigan. He is employed as a Research Geologist at the Environmental Research Institute of Michigan where he is engaged in Remote Sensing research in geologic applications and in technology transfer. He has designed digital processing software systems which are now in use in numerous countries throughout the world.

ABSTRACT

Directional trends in digitized images or topographic data can be enhanced with arbitrary acceptance or rejection angles. The enhanced results are similar to those produced in directional two-dimensional FFT filtering, but with no filter "ringing" and in substantially less computing time than that required for the FFT filter. The gradient filter operates by applying acceptance, rejection or weighting criteria based on the angle between the direction of the gradient and the perpendicular to the trend direction.

INTRODUCTION

Finding the direction of trends in images or topographic data is useful in several disciplines. Two examples are the direction of slopes for water runoff in hydrology, and the direction and location of "linears" which might indicate faults, fracture zones or synclinal structures in geology. A digital method which makes use of the direction of the gradient can produce trend-filtered images in approximately 1/20 the computing time required for directional FFT filtering. No filter effect is produced in the image, and filter weighting can be included.

Currently directional filtering is performed both digitally or optically by convolution in the space domain or attenuation in the frequency domain. Convolution is equivalent to using a line spread function (Rosenfeld, 1969), an m x n rectangular averaging (Chavez, et al., 1976), viewing with a square wave transmission grating in

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which diffraction is used (Pohn, 1970), or electronic displacement of positive and negative images (Podwysocki, et al., 1975). The latter technique is a form of "edge spread function" (Rosenfeld, 1969).

Directional filtering in the frequency domain is performed both digitally and optically by obtaining a two-dimensional Fourier transform of the data, and selectively attenuating before retransforming. This technique has been applied to seismograms and contour maps (Embree, et al., 1959; Jackson, 1965) and on radar imagery (Eppes and Rouse, 1971), who examined the distributions in the transform.

Directional trends can also be enhanced by finding the slope (directional derivative) in a selected direction and simulating an illuminating sun and viewing angle (Batson, et al., 1975). The Batson technique was employed for contour map data, but is also useful on Landsat and radar imagery (Wagner and Jackson, 1979). A wide angular passband for lineaments falls off as the cosine from the perpendicular to the direction of the simultated sun. Effectively it produces a very narrow stop band for lineaments in the direction of the sun.

The gradient is also employed by edge enhancement by replacing the image values by the magnitude of the gradient (Rosenfeld, 1969), e.g., by

$$|\bar{G}| = [(\partial f/\partial x)^2 + (\partial f/\partial y)^2]^{1/2} \qquad (1)$$

where G is the gradient and f is the image function f(x,y). This replacement, and similar replacement by the Laplacian (second derivatives), "sharpens" an image and is used to bring out lineations in the image, although no directionality is included.

Our technique uses the gradient in a manner which is more directionally sensitive and controllable than a single directional derivative, and results in no filter ringing as in Fourier transform filtering. The direction of the gradient θ_G is easily found. It is the arctangent of the ratio between the directional derivative in the y direction and that in the x direction.

$$\theta_G = \arctan\left(\frac{\partial f/\partial y}{\partial f/\partial x}\right) \qquad (2)$$

θ_G will be perpendicular to a linear trend, and will lie within an angle about the average perpendicular to a sinuous or jagged trend.

The direction for filtering is first selected for the desired trend enhancement. The direction of the gradient can be computed by Equation (2). Filtering can then be performed on the basis of the angular relationship between the selected direction and the direction of the gradient. These types include charp cutoff passband and stopband, and weighting of any kind ($\cos^2$, exponential, etc). The angle of directional passband or stopband can be made as narrow or wide as desired. Because no convolution between the filtered data and the filter occurs there is no filter ringing.

DESCRIPTION

For a feature to have a trend in any direction it must have gradients within an angular range about the perpendicular direction. This is true of images, of contour maps, and of actual topography as in ridges and valleys. These objects can be represented by the two-dimensional function

$$I = f(x,y) \tag{3}$$

where (x,y) is the location on a two-dimensional plane, and f is the value representing elevation, reflection or other parameter at each location in the plane. The gradient is

$$\overline{G} = \nabla f = (\partial f/\partial x)\ \overline{i} + (\partial f/\partial y)\ \overline{j}$$

where $\overline{i}$ is a unit vector in the x direction,

$\overline{j}$ is a unit vector in the y direction, and

$\partial f/\partial x$ and $\partial f/\partial y$ are the slopes in the x and y directions.

The direction of the gradient is conventionally defined as the resultant of the slopes (also called "directional derivatives") in the x and y directions. The gradient also can be defined as the resultant of the slopes in any two directions which are perpendicular to each other (Kaplan, 1957). To define the gradient, we can therefore first find the slope in any arbitrary direction, then find the slope in the perpendicular direction, and from these two slopes compute the gradient. In digital computing, where the image is stored in a two-dimensional matrix, it is convenient to use the row and column directions to compute the gradient.

For conceptual purposes the general algorithm for pass-band gradient filtering is developed as follows.

Consider a two-dimensional function as in Eq. (3), and define the angles between the positive x-axis and a given direction to be in a counterclockwise direction. Select the direction θ_p which is perpendicular to the average direction of the trend to be enhanced, and the angular increment $\Delta\theta$ which it is desired to pass in the filter. This passband will then have the angular limits of

$$\begin{aligned} \theta_\ell &= \theta_p - 1/2\Delta\theta \\ \theta_m &= \theta_p + 1/2\Delta\theta \end{aligned} \tag{4}$$

We treat both positive and negative slopes as being in identical directions, because the positive slope on one side of a trend defines the trend in the same way as a negative slope on the other side of the trend.

The gradient direction is computed simply by Eq. (2) which in a two-dimensional digital format can be approximated most simply by

$$\theta g = \arctan\left(\frac{I(i,j) - I(i,j+1)}{I(i,j) - I(i+1,j)}\right) \qquad (5)$$

where I is the intensity of the pixel indexed by column i and row j of the image array.

To pass the filter the following condition must hold:

$$\theta_\ell \le \theta_g \le \theta_m \qquad (6)$$

The setting of the limits (4), computation of Eq. 5, and selection for display only those sampled data which conform to condition (6), comprise the gradient passband filtering algorithm.

The above, presented in angles for conceptual purposes, can be made more efficient by specifying the limits in terms of tangents rather than angles, so that the arctangent does not require computation for each sample of the image. In this case Eq. (6) can be replaced by

$$\tan \theta_\ell < \frac{\partial f/\partial y}{\partial f/\partial x} \le \tan \theta_m. \qquad (7)$$

with suitable care for the polarity of the tangent in the different quadrants.

After filtering, one can choose to select the original data (elevation, intensity, etc.) or the slope itself to produce a computer-enhanced image synthesizing a view with a sun angle (Batson, et al., 1975), or any other representation of the data, such as the Laplachian (Rosenfeld, 1969).

A passband filter was described. However, with the filtering conditions fulfilled, one could produce many kinds of filters. By merely passing all elements which do not conform to condition (6) and rejecting those which do conform to condition (6), a stopband filter is produced. By using the relationship between θ_g, θ_ℓ, and θ_m, weighting ($\cos^2$, exponential, Gaussion, etc.) could be achieved. By attenuating rather than eliminating the data in the stopbands, a subdued background of the non-trending image could be displayed against the enhanced trends. If color is available, the passed trends could be displayed in one color, and the rejected trends in another, or different trends could be represented by different colors in an image.

ILLUSTRATIONS

Figure 1a is a computer-drawn perspective plot of a function which has equal slopes in all directions.

Figure 1b is a plot of the function shown in Figure 1a after it has been gradient-filtered. The filter was oriented N65°E with a directional passband of 40° (±20°). North is parallel to the direction of the base lines in the plot.

Figure 1c is a plot showing the effect of using a stopband rather than a passband. Otherwise all parameters and conditions are identical to Figure 1b.

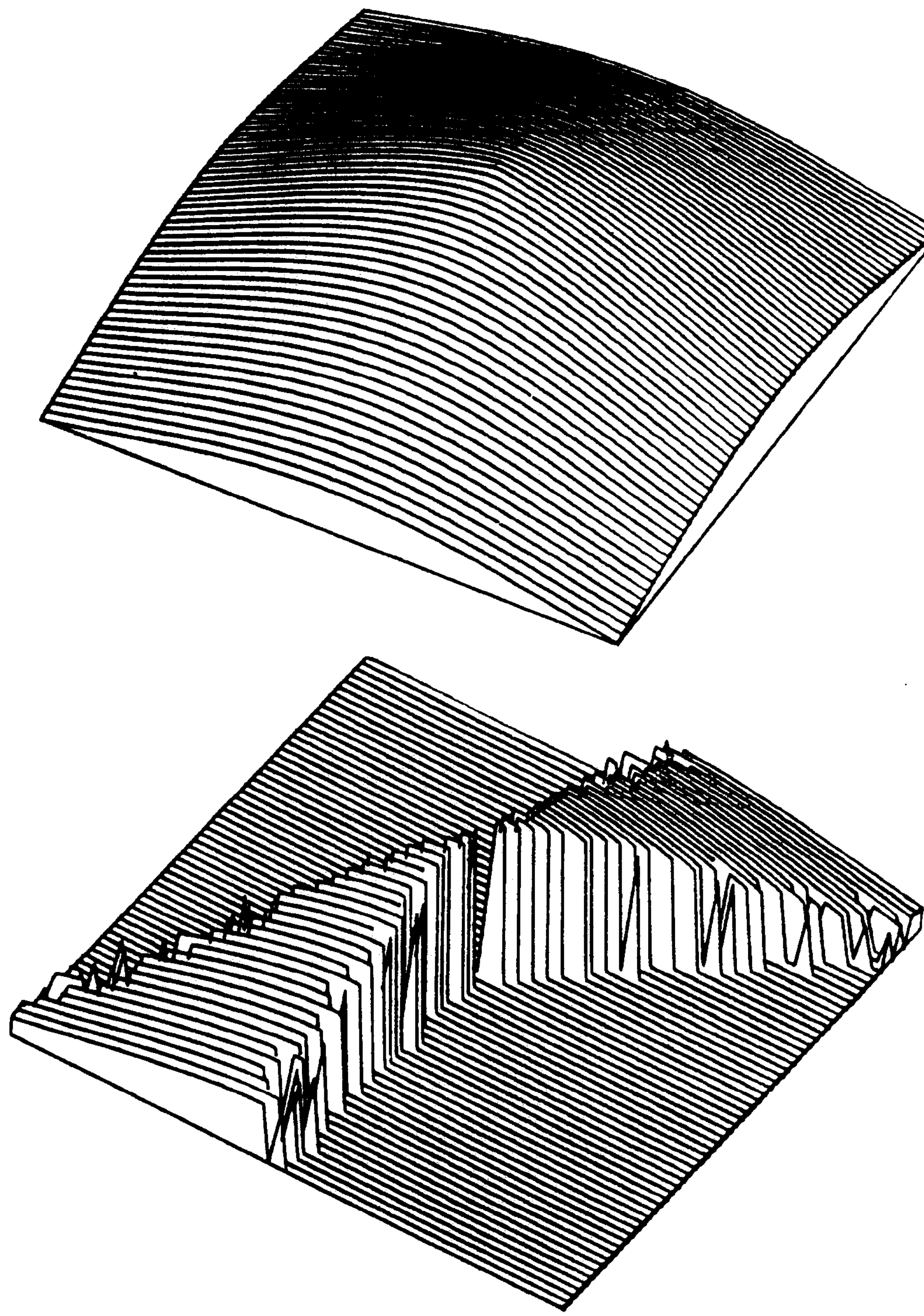

FIGURE 1. (a) (b). GRADIENT FILTERING OF AN ARBITRARY FUNCTION WHICH HAS EQUAL MAGNITUDE OF SLOPE IN ALL DIRECTIONS. (a) Unfiltered Function. (b) Gradient filtering with passband at $65^\circ + 20^\circ$ to direction of reference lines. (Figure 1 continued on following page.)

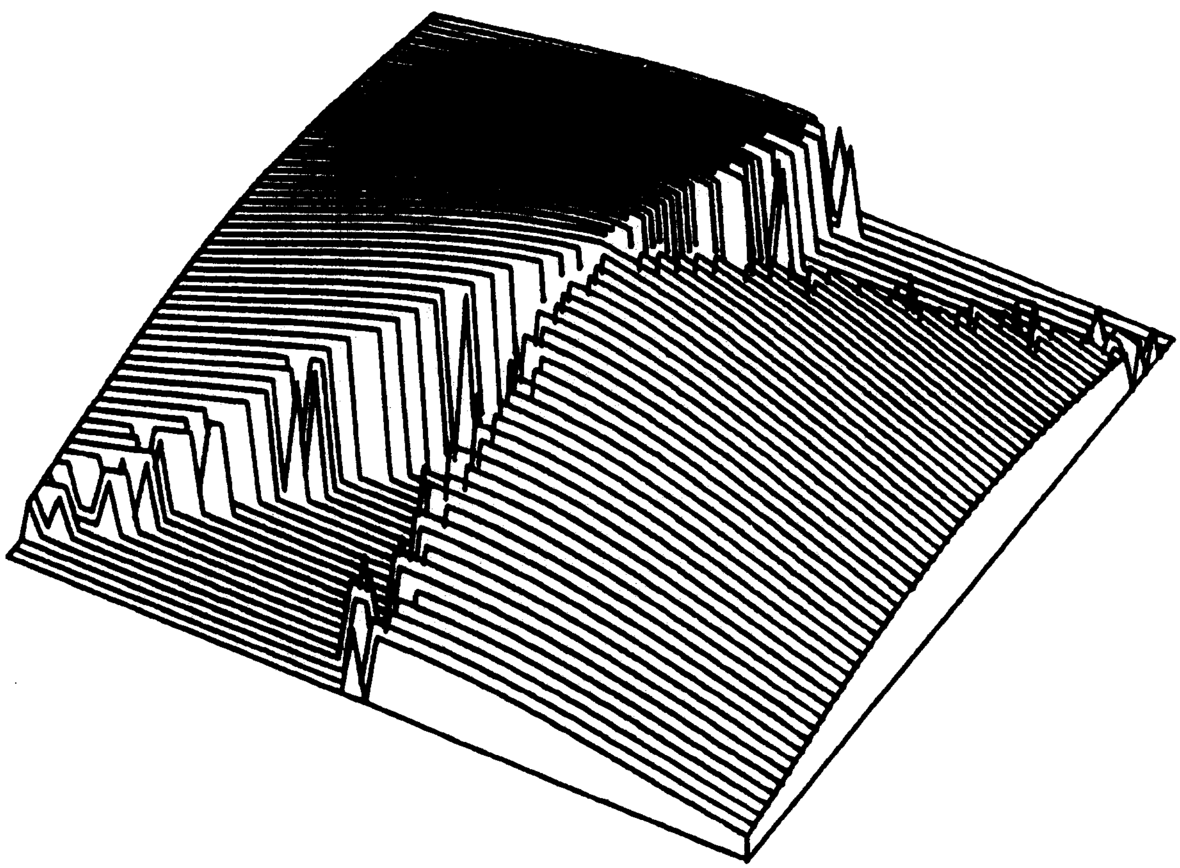

FIGURE 1. (Continued). GRADIENT FILTERING OF AN ARBITRARY FUNCTION WHICH HAS EQUAL MAGNITUDE OF SLOPE IN ALL DIRECTIONS. (c) Gradient Filtering with Stopband at $65^{\circ}+20^{\circ}$ to Direction of Reference Lines.

Figure 2a is an unfiltered SAR image of a region between Ripley, West Virginia and the Ohio River which includes the Cottageville gas field.

Figure 2b shows the SAR image of Figure 2a after gradient filtering with a $\pm$ 45° wedge to bring out lineaments in the NE-SW direction. After filtering a sun was simulated from the SW and the Lommel-Seegler equation was applied (Batson, et al., 1975).

Figure 2c shows the SAR image of Figure 2a after gradient filtering with a $\pm$ 45° wedge directed in the NW-SE direction, with a sun simulated from the NW direction.

DISCUSSION

Figures 1 and 2 illustrate the directional filtering capabilities of the gradient. The method has been shown to be effective on both simulated and actual data. The noise along the edges of the passband in Figure 1a and the stopband in Figure 1c arose from computations using integer arithmetic.

Two separate problems arise on SAR and Landsat data: noise on individual pixels can produce erroneous results on four pixels, as each pixel is used in the computation of four gradient values. Also integers representing pixel intensities often have a contrast of only a few digital counts between adjacent pixels, producing coarse directional definitions.

Noise is reduced by smoothing the data. A 3 x 3 smoothing provided the best compromise between noise reduction and resolution retention on Landsat and SAR data. The integer problem is reduced by including multiplicative scaling in the smoothing algorithm so that the output is expanded and scaled before conversion back to an integer form.

CONCLUSIONS

Using the gradient, directional filtering can be performed on digitized imagery. The direction of the filtering and the angular size of the passband or stopband can be easily specified, and weighting could be performed. The filtered image is similar to that produced by two-dimensional Fourier transform filtering. However, the gradient filter does not cause ringing and, for a 128 x 128 pixel image, requires approximately 1/20 of the computing time required in Fourier transform filtering. As the computing time for gradient filtering is directly proportional to the number of pixels, entire Landsat frames can be economically filtered.

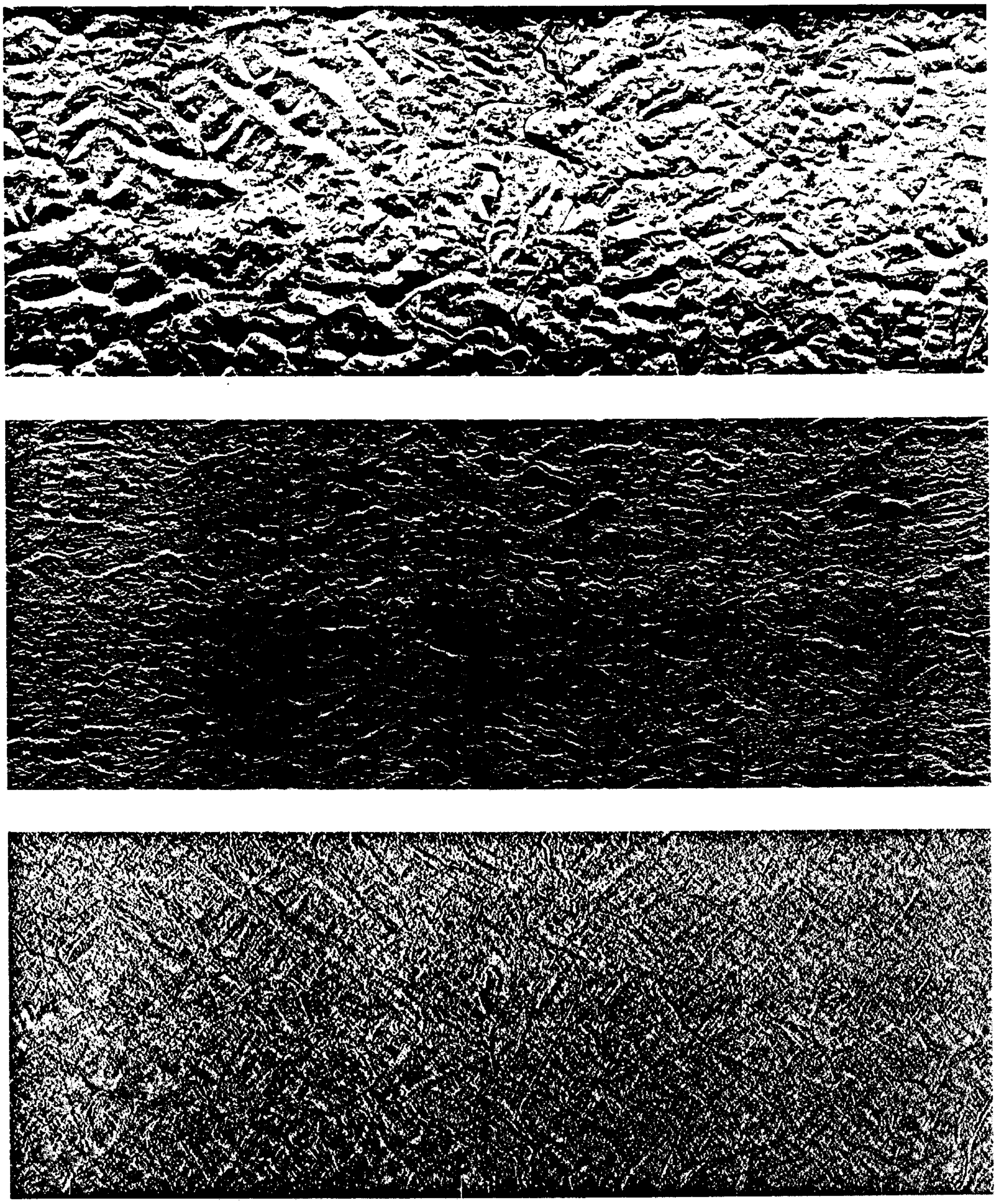

FIGURE 2. GRADIENT FILTERING OF A SYNTHETIC APERTURE RADAR IMAGE OF COTTAGEVILLE, WEST VIRGINIA AREA. (a) Unfiltered Image. (b) Image filtered in NE-SW Direction, +45° Passband. (c) Image filtered in NW-SE direction, +45° passband.

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